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AFAPL-TR-78-104

150 KVA SAMARIUM COBALT VSCF STARTER/GENERATOR ELECTRICAL SYSTEM FINAL TECHNICAL REPORT

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GENERAL ELECTRIC COMPANY
AIRCRAFT EQUIPMENT DIVISION
BINGHAMTON, N. Y.

DECEMBER 1978

TECHNICAL REPORT AFAPL-TR-78-104

REPORT FOR PERIOD 1 JUNE 1974 - 31 MAY 1978
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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFAPL-TR-78-104	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): 150 KVA SAMARIUM COBALT VSCF STARTER GENERATOR ELECTRICAL SYSTEM FINAL TECHNICAL REPORT	5. TYPE OF REPORT & PERIOD COVERED: Final 1 June '74 to 31 May '78
	6. PERFORMING ORG. REPORT NUMBER: AES 11,730
7. AUTHOR(s): Lafuze, David L.; Webb, Robert C.; Triebel, Charles F.; Brissey, George E.; Foss, Albert C.	8. CONTRACT OR GRANT NUMBER(s): F33615-74-C-2037
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Aerospace Controls and Electrical Systems Dept. General Electric Company Box 5000, Binghamton, New York 13902	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 62203F-3145-29-48
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Aero Propulsion Laboratory Aerospace Power Division - Vehicle Power Branch/POP Wright Patterson Air Force Base, Ohio 45433	12. REPORT DATE: December 1978
	13. NUMBER OF PAGES: 191
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release
Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

David L. /Lafuze, Robert C. /Webb, Charles F. /Triebel, George E. /Brissey Albert C. /Foss

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Samarium Cobalt Magnets
Starter-Generator
Variable Speed Constant Frequency (VSCF) Electric System

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report documents the development, construction and test of a 150 KVA Starter/Generator Variable Speed Constant Frequency (VSCF) electrical system which includes a solid rotor machine using rare earth samarium cobalt magnets. The system consists of the solid rotor 14-pole starter/generator which in the generate mode, is driven at 12,000 to 21,000 RPM and a cycloconverter which, converts the 9-phase variable frequency power from the generator to a high quality 3-phase, 400 Hz.

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150 KVA power source. In the start mode, the cycloconverter converts 3-phase, 400 Hz power to a 9-phase variable frequency, variable voltage which is used to power the starter/generator as the equivalent of a brushless DC motor. The rotor was developed during the first phase of the program which is reported on in detail in AFAPL-TR-76-8. The generator is oil cooled and uses a self contained oil pump. It also includes a high speed mechanical disconnect which is solenoid operated to remove drive power and is mechanically reset at zero speed. The stator core uses 0.006 inch permendur laminations to handle high flux densities with a minimum of eddy current losses. The cycloconverter uses a dip brazed chassis, with liquid (oil) cooled cold plates for heat extraction. The major volume in the converter houses the power handling components which include 54 SCRs, 18 interphase transformers, 15 output filter capacitors and input despiker components. System test data shows a high generate mode efficiency of 88% at rated load which falls off to 73.5% at one quarter load. Start mode has a torque output above 1800 in lb. out to approximately 6000 RPM.

PREFACE

This report documents phase II and III of the design, development, construction and test of a 150 KVA Starter/Generator Variable Speed Constant Frequency (VSCF) electrical system which includes a solid rotor machine using rare earth Samarium Cobalt Magnets. The system is designed to provide 3-phase 400 Hz power rated at 150 KVA in the generate mode and provide torque output to start a 50,000 lb. thrust class engine in the start mode. The Phase I effort on the program is documented in detail in AFAPL-TR-76-8.

This final report was submitted by the General Electric Company, under contract F33615-74-C-2037. The effort was sponsored by the Air Force Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright Patterson AFB, Ohio under Project 3145, Task 314529 and Work Unit 31452948 with Paul R Bertheaud/AFAPL/POP-2 as Project Engineer. The major technical contributors to these phases of the contract were G.E. Brissey, A.C. Foss, D.L. Lafuze, A.B. Osborne, C.F. Triebel and R.C. Webb of the General Electric Company.

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SECTION I

INTRODUCTION

Aircraft electrical starter/generators presently utilize carbon brushes to conduct power to the rotor of wound rotor machines. These machines encounter the usual problems associated with operating brushes on high altitude aircraft. The development of rare earth permanent magnet technology has provided a means of obtaining power densities in a permanent magnet generator equivalent to those found in an electrically excited generator, and therefore a method to eliminate the use of brushes. This development will result in significant improvements in both the reliability of the rotating hardware and the reduction of system production costs.

USAF Contract No. F33615-74-C-2037 defines a program to demonstrate the feasibility of applying a samarium cobalt permanent magnet generator (PMG) to a VSCF starter/generator system. The permanent magnet generator will function as the source of the system's electrical power and as an electric motor when the system is in the starting mode of operation.

The program is divided into three phases which are summarized as follows:

Phase I - Preliminary System Design, Samarium Cobalt Rotor Fabrication and Test

Phase II - Fabrication of Laboratory Prototype Starter/Generator and Cycloconverter/Control Unit

Phase III - Component and System Evaluation Test

This report is the final technical report of the program. It covers the activity of the entire program but two more detailed reports on specific early parts of the program are listed below for convenience.

Subject	Reference
Subsystem Design Analysis	Data Item A003 September 6, 1974
Technical Report Phase 1 Development Fabrication and testing of the Samarium Cobalt Rotor	AFAPL-TR-76-8 March 1976

This final report reviews the system design concept and the rotor construction and then proceeds with a detailed description of the system design, the generator design and the cycloconverter design. Section 5 provides a description of two major faults, their cause and corrective action. Each of these faults destroyed the stator but the samarium cobalt rotor was not damaged.

Section 6 provides the test data taken on the generator as a unit and in the system. The system test data covers operation in Start mode and generate mode including 1.5 PU and 2.0 PU overloads, transient response line faults, protection circuits and parallel operation.

SECTION II

SUMMARY

2.1 INTRODUCTION

All three phases of the program with respect to the hardware are completed. Phase I was completed in December 1975 with the completion of rotor spin testing and shock tests. The last data item specifically associated with Phase I (Final Technical Report (Phase 1)) was submitted in March 1976. Go ahead for Phase II and III was received in December 1976 and at that time the Phase III hardware delivery was expected to be in the first quarter of 1977. A generator fault in 1976 and a system fault in 1977 each had significant schedule impact on the program, however, the Phase III hardware delivery was rescheduled for 31 May 1978 which is the actual shipment date. This report covers the full program but concentrates on the activity in Phase II and III since the Phase I activity is well documented in the reports listed in Section 1.

2.2 ROTOR DESIGN CONFIGURATION

The solid rotor shown in Figure 1 is constructed by assembling seven 6.5 inch diameter 1 inch long discs on a 3-5/8-inch diameter hollow shaft. Figure 2 is a drawing of the rotor showing these discs. Each disc assembly contains 14 samarium cobalt magnets wedged between pole pieces and a bimetallic shrink ring which encapsulates the assembly. A photograph of one of these assemblies (Serial Number 019) used in the rotor is shown in Figure 3. The shrink ring holds the magnets and pole pieces in compression up through the overspeed rating (23,100 RPM) of the rotor to minimize the affect of cyclic fatigue. This shrink ring is constructed of 28 alternately magnetic and non-magnetic segments which are electron beam welded together. The magnetic segments are located over the pole pieces to shorten the magnetic airgap in the machine and the non-magnetic segments located over the magnets are required to prevent a magnetic short between pole pieces. A photograph of one of the shrink rings fabricated during Phase I is shown in Figure 4.

The first major effort after establishing the design configuration was selection of materials, joining and forming methods to fabricate a shrink ring with sufficient tensile strength to contain the magnets and pole pieces up through the overspeed rating of the rotor. The chosen process uses maraging steel as the magnetic segment and MP35N as the non-magnetic segment. These are joined by electron beam welding and cold worked and formed to obtain the required strength and shape.

The pole and magnet assembly is fabricated by first electron beam welding a low carbon steel donut to an inner hub of Inconel. Slots are then machined in the low carbon steel to accept the samarium cobalt magnets. The magnets are then wedged in place and the pole and magnet assembly is machined to proper dimension. The steps in this process are illustrated in Figure 5.

The shrink ring is then assembled to the pole and magnet assembly by heating it to 1000°F while cooling the pole and magnet assembly to approximately -150°F.

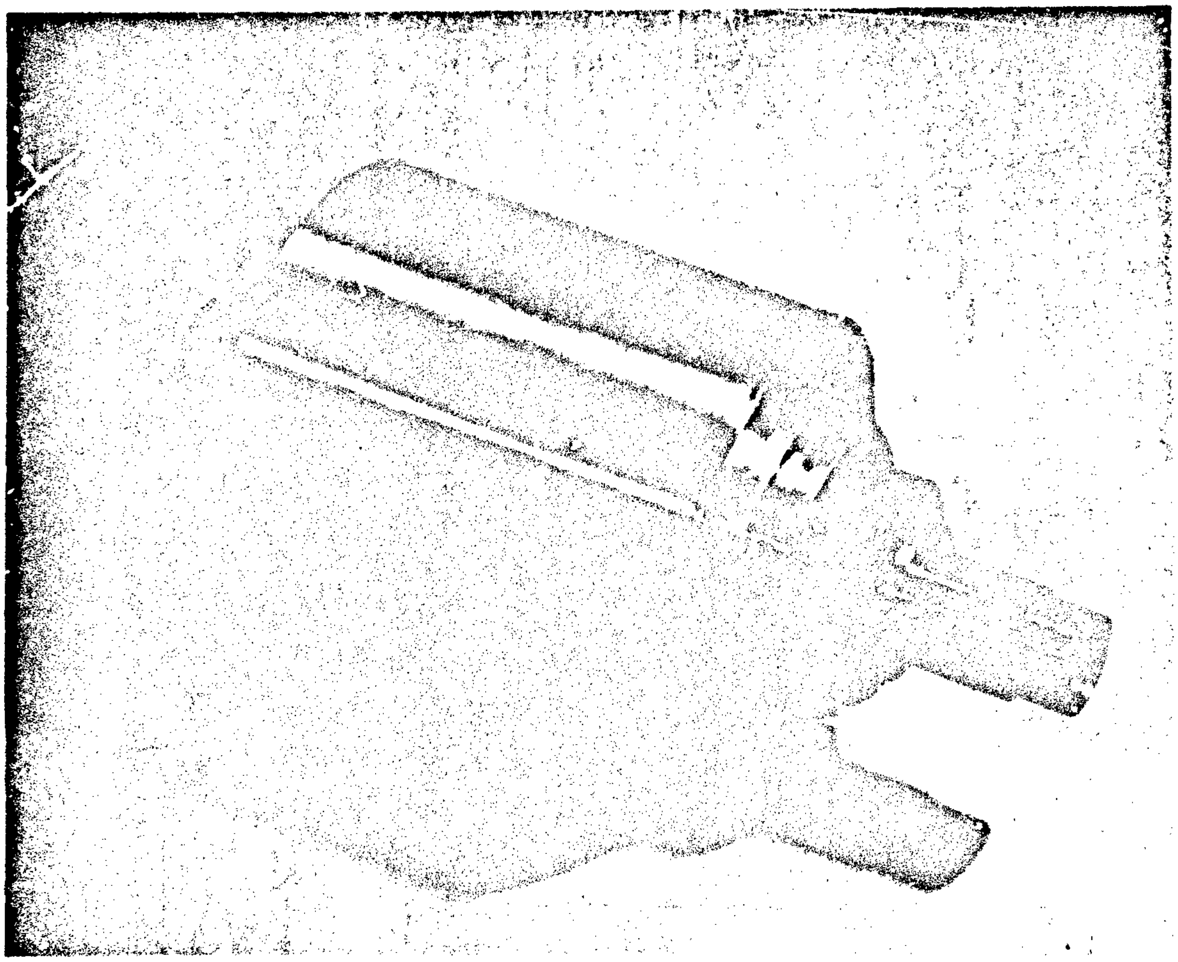


Figure 1. Samarium Cobalt Permanent Magnet Solid Rotor

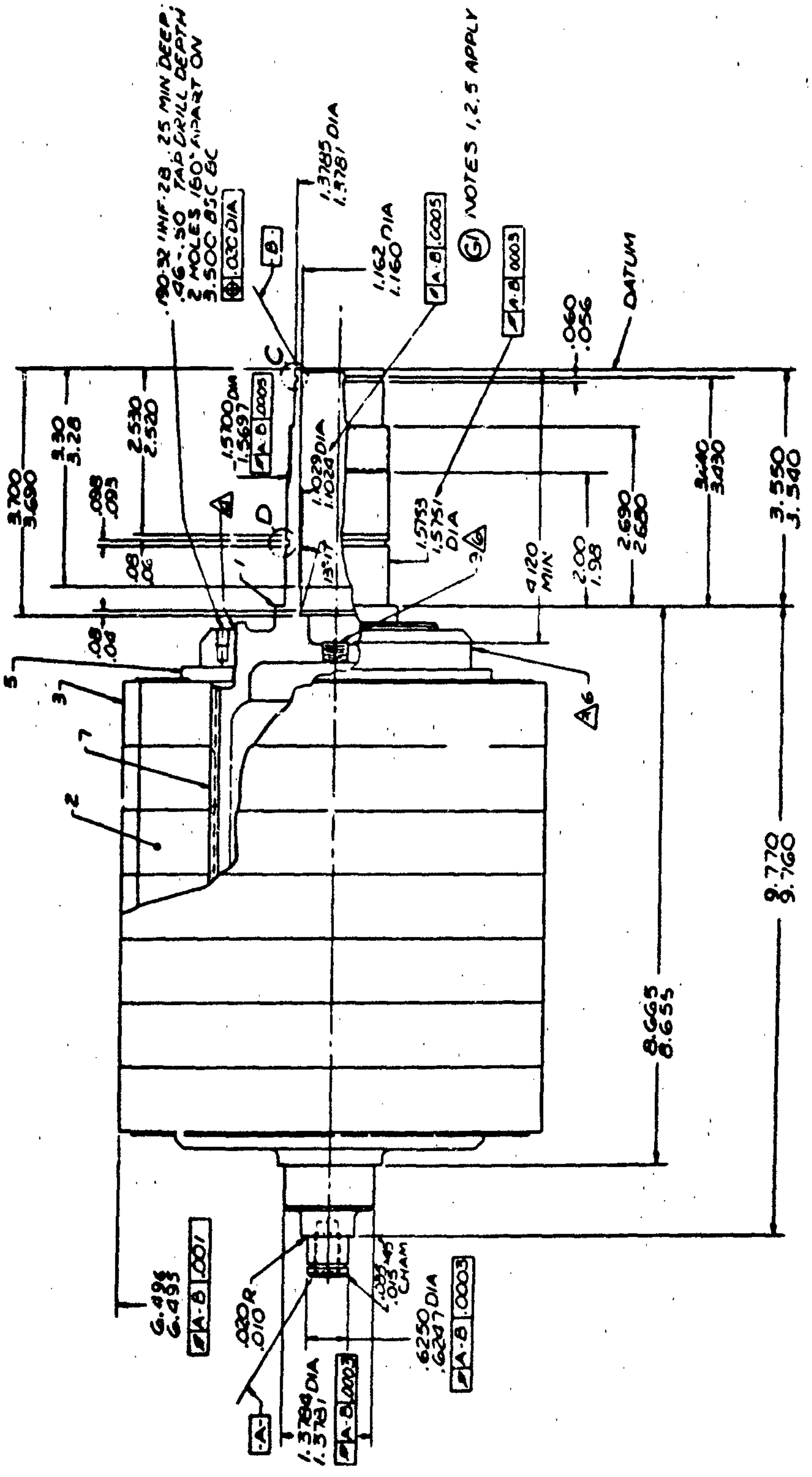


Figure 2. Rotor Drawing

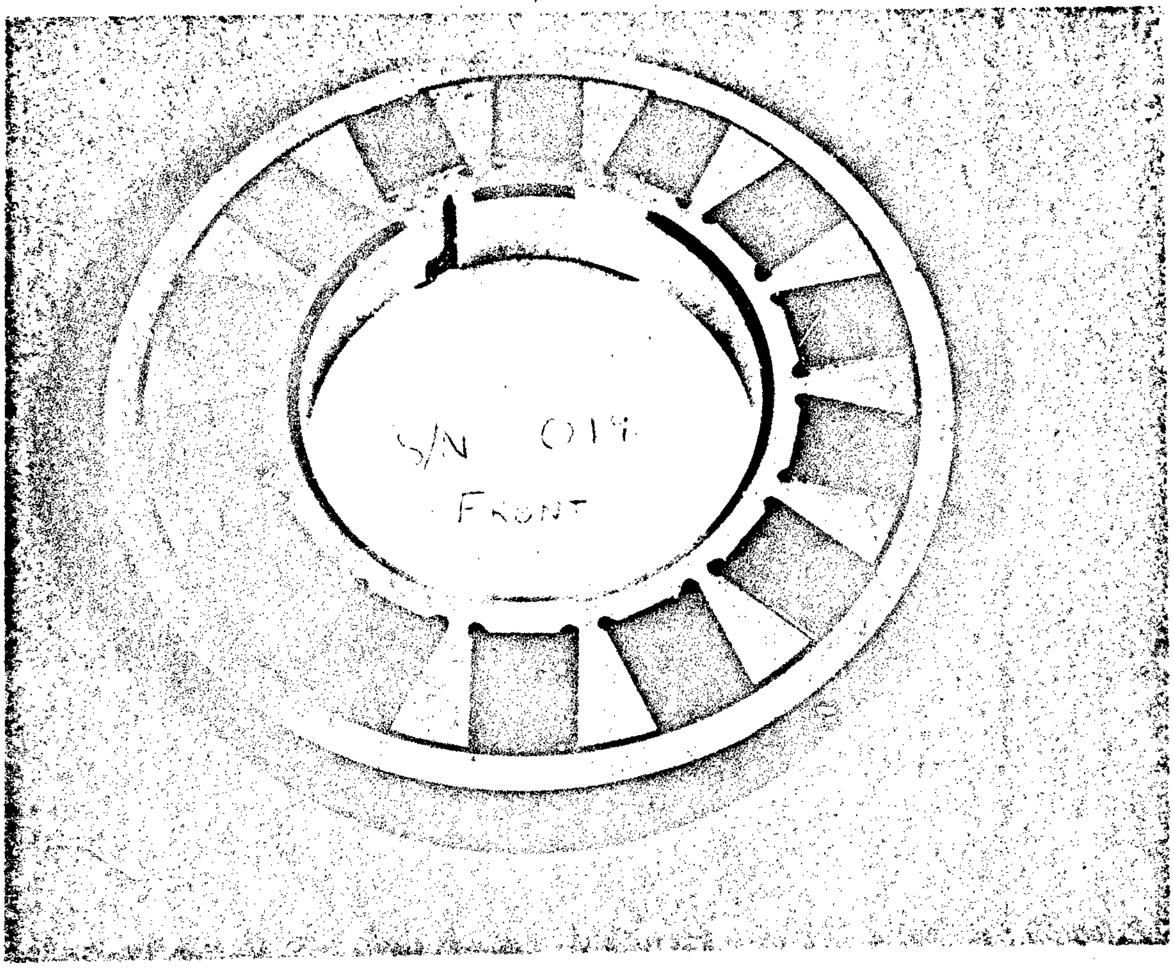


Figure 3. Rotor Disc

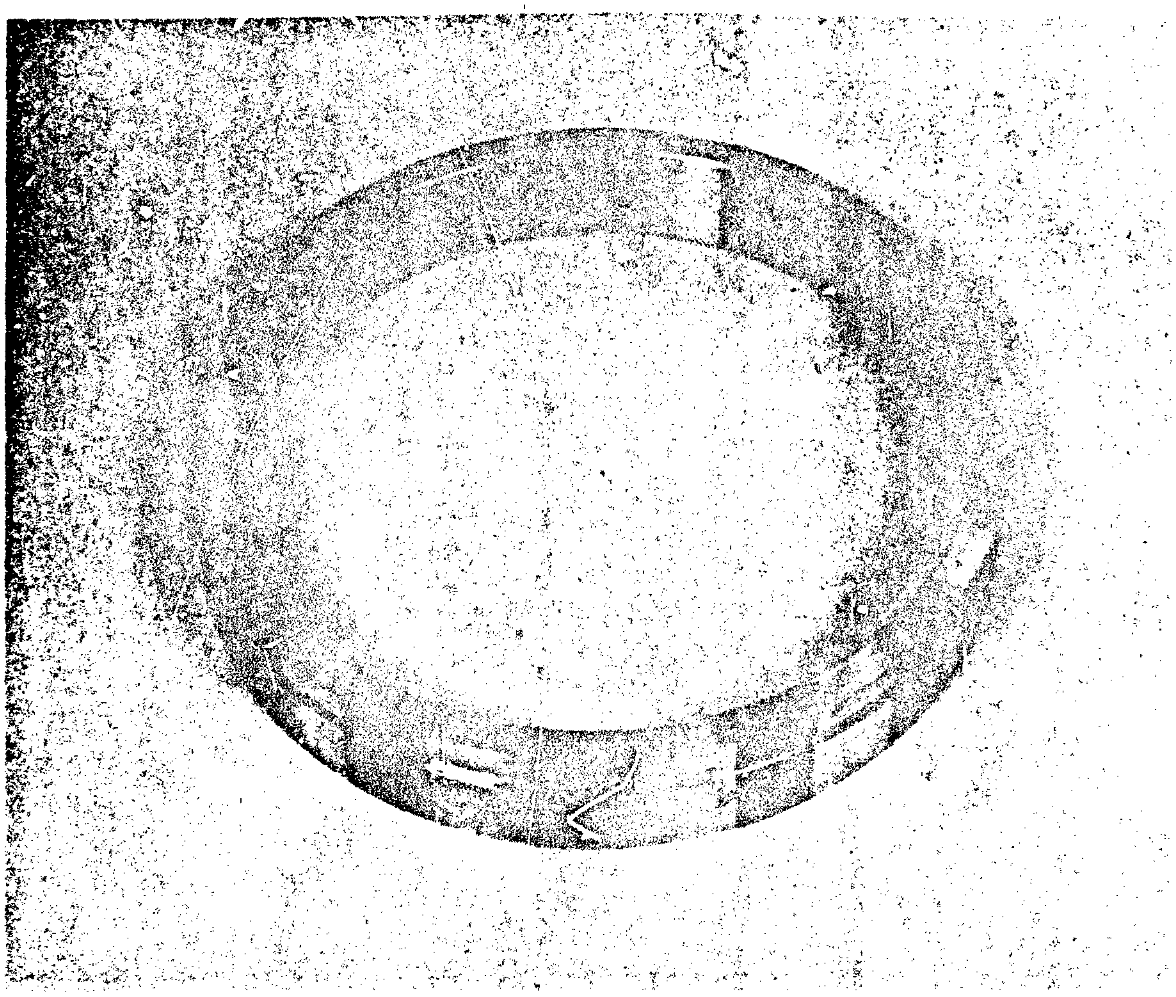


Figure 4. Shrink Ring

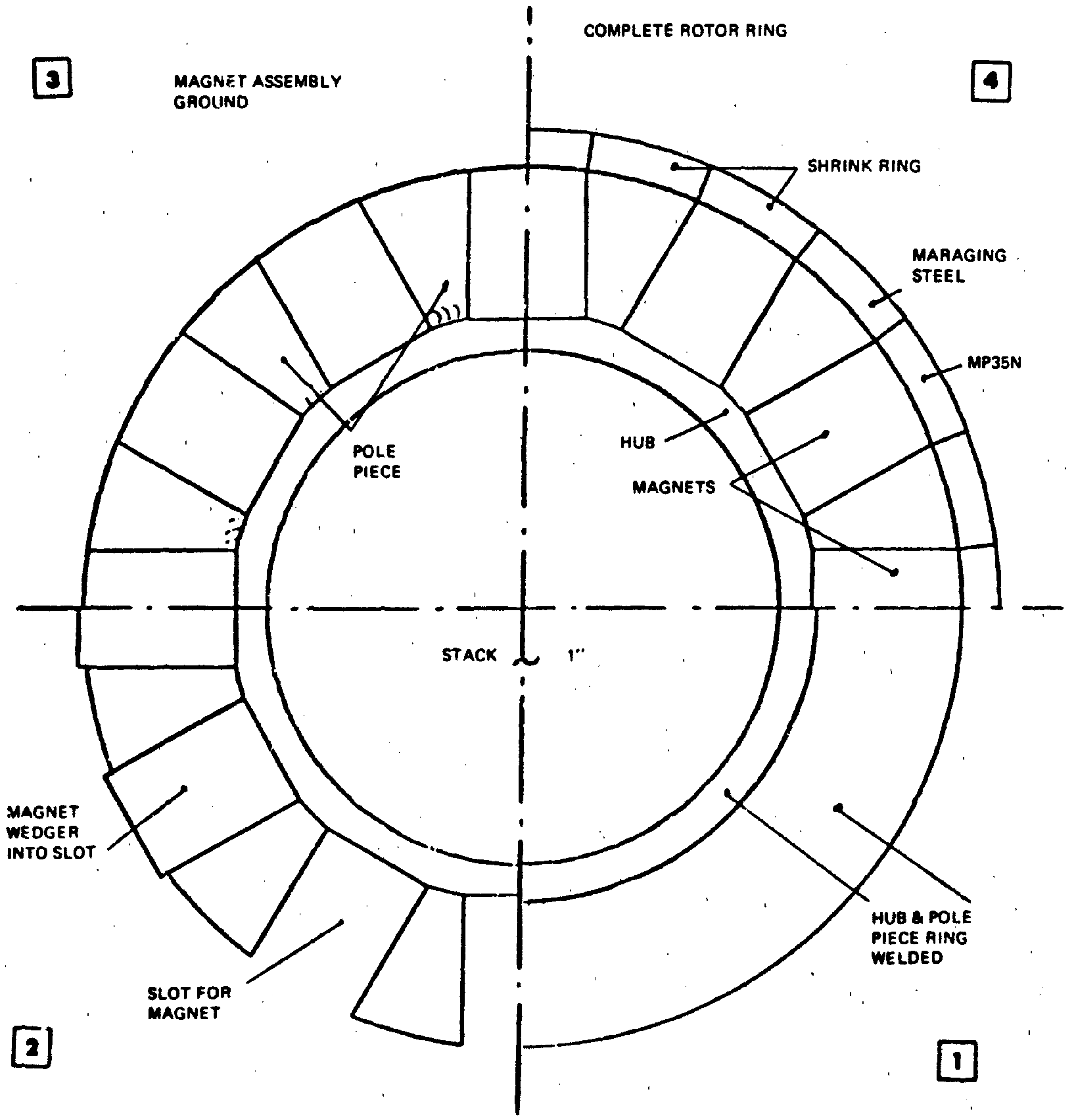


Figure 5. 150 KVA PMG Disc Construction

The disc assemblies are assembled to the shaft by cooling the shaft in liquid nitrogen and pressing it into all seven disc assemblies at once while they are held in an aligning fixture.

2.3 STARTER/GENERATOR DESIGN CONFIGURATION

The starter generator uses the 14 pole samarium cobalt rotor in a nine phase output stator. The stator is housed in an aluminum frame along with a self contained lubricating and cooling oil flow pump, a high speed mechanical disconnect and a Hall probe assembly which is used to sense rotor position in start mode. Figure 6 is a photo of this starter generator mounted on a drive stand. Figure 7 is a cross section of the starter generator with the major assemblies identified. A detailed description of the starter generator is provided in section 4.2 with many photographs of these assemblies.

2.4 CYCLOCONVERTER DESIGN CONFIGURATION

The cycloconverter designed and delivered on this program is shown in Figure 8. This uses 54 Silicon Controlled Rectifier (SCRs) to convert the nine phase of variable frequency power from the generator into a 3 phase 400 Hz output. In the start mode these SCRs convert the 3 phase 400 Hz input power into a variable frequency output to the machine.

The cycloconverter uses a dip brazed chassis with liquid (oil) cooled cold plates for heat extraction. The major power handling components which are mounted on cold plates in the converter include the 54 SCRs, 18 interphase transformers and the input despiker components. Two small fans were added later during testing to provide additional cooling for the copper in the interphase transformer.

2.5 TEST RESULTS

Generate mode testing verified the predicted high efficiency of the system in both generate mode and start mode. In generate mode the overall efficiency from mechanical drive power to the 400 Hz power delivered to the load was measured at 88% at rated load and dropped off to 73.5% at one quarter load. Overall start mode efficiency at 2400 RPM and above is 70% or higher. The torque at low speed out to 6000 RPM is 150 lb-ft. This is lower than the 190 lb-ft goal at stall and out to 4000 RPM requirement but this is partially due to a mismatch of the starter operating speed relative to the idle speed of the engine. Figure 9 shows the measured starting torque versus starter shaft speed, the specified required engine start torque and the required engine start torque reflected to the starter shaft through a 4/3 ratio gear box. Note that with the gearbox to accommodate the speed mismatch the measured torque exceeds the requirement by a comfortable margin.

The heat dissipated in the rotor due to windage losses and rotor pole face losses was understimated in the early machine design phase. Early measured thermal data on the machine revealed much higher windage losses then anticipated. These combined with calculated pole face losses indicated a rotor heating problem at high speed. Rather than add cooling oil to the rotor it was decided to proceed with the machine as designed and limit the top speed to avoid overheating the samarium cobalt magnets.

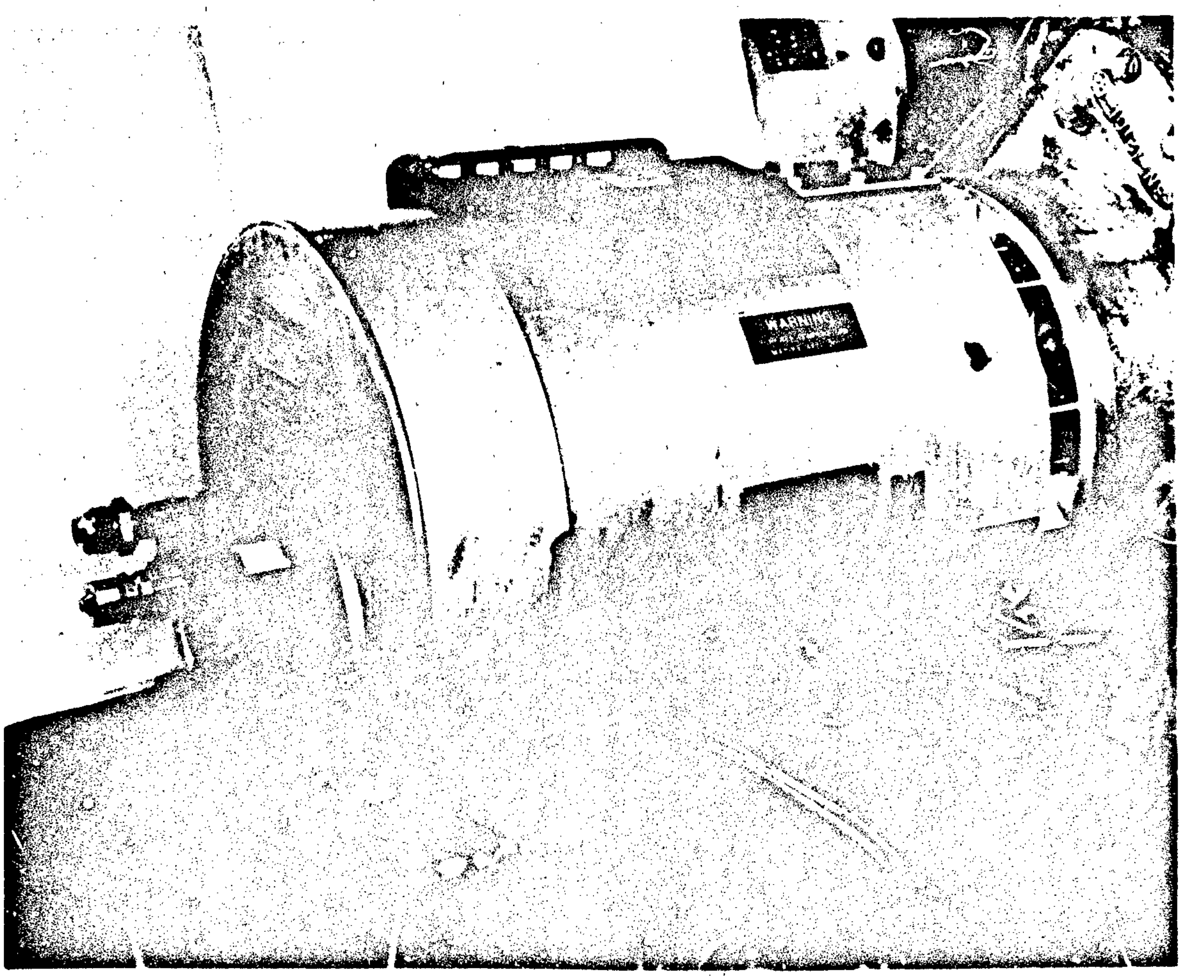


Figure 6. Starter/Generator Drive Stand

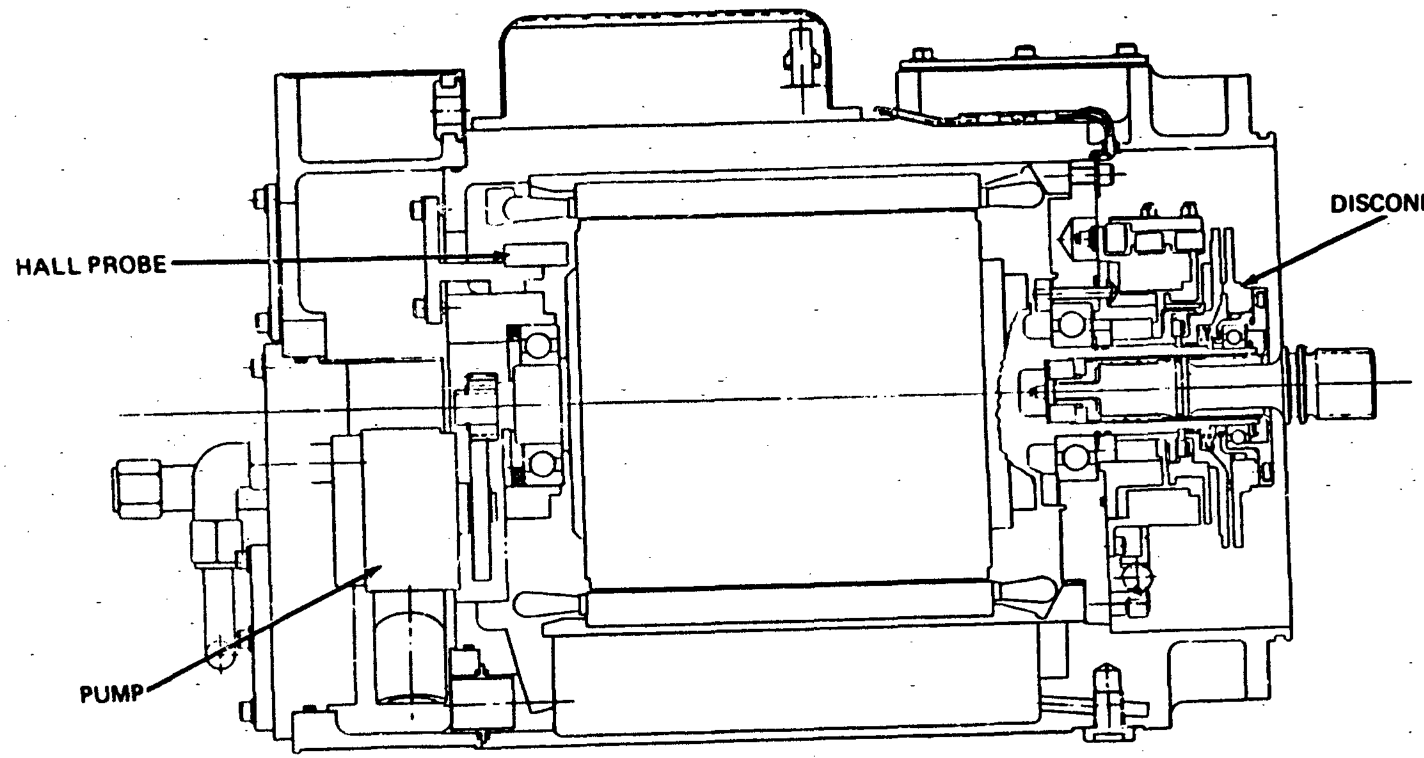


Figure 7. Generator Cross Section

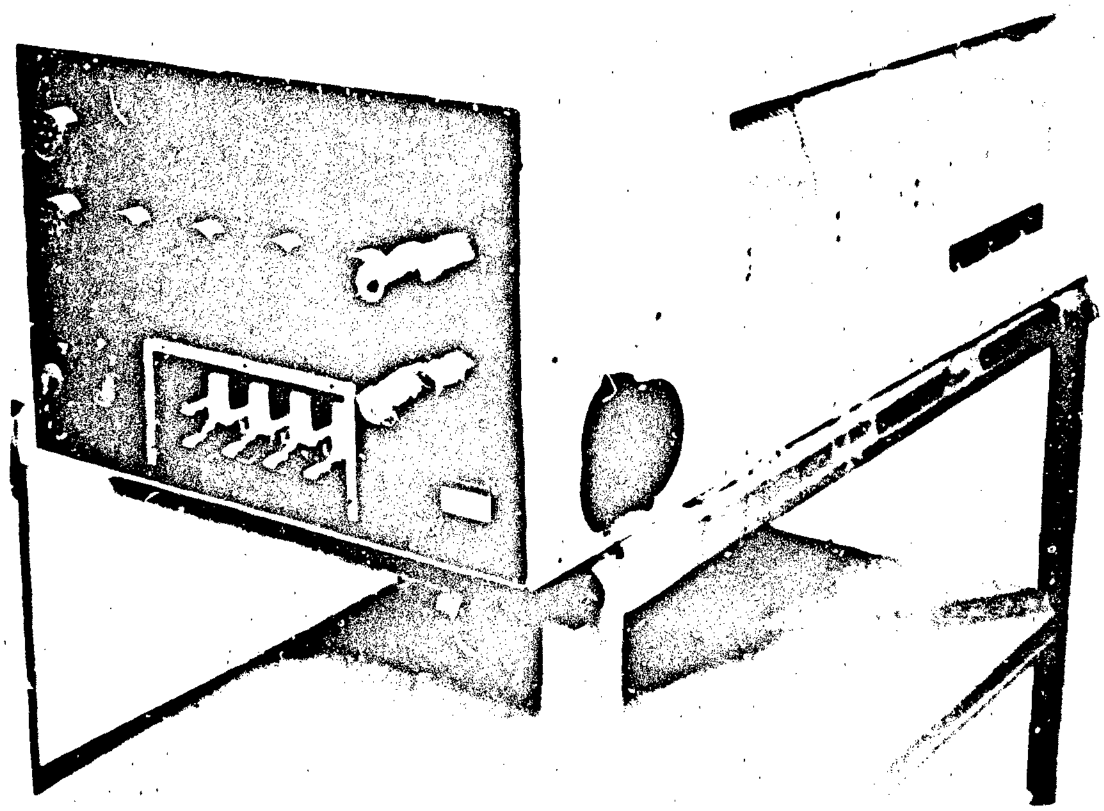


Figure 8. Cycloconverter

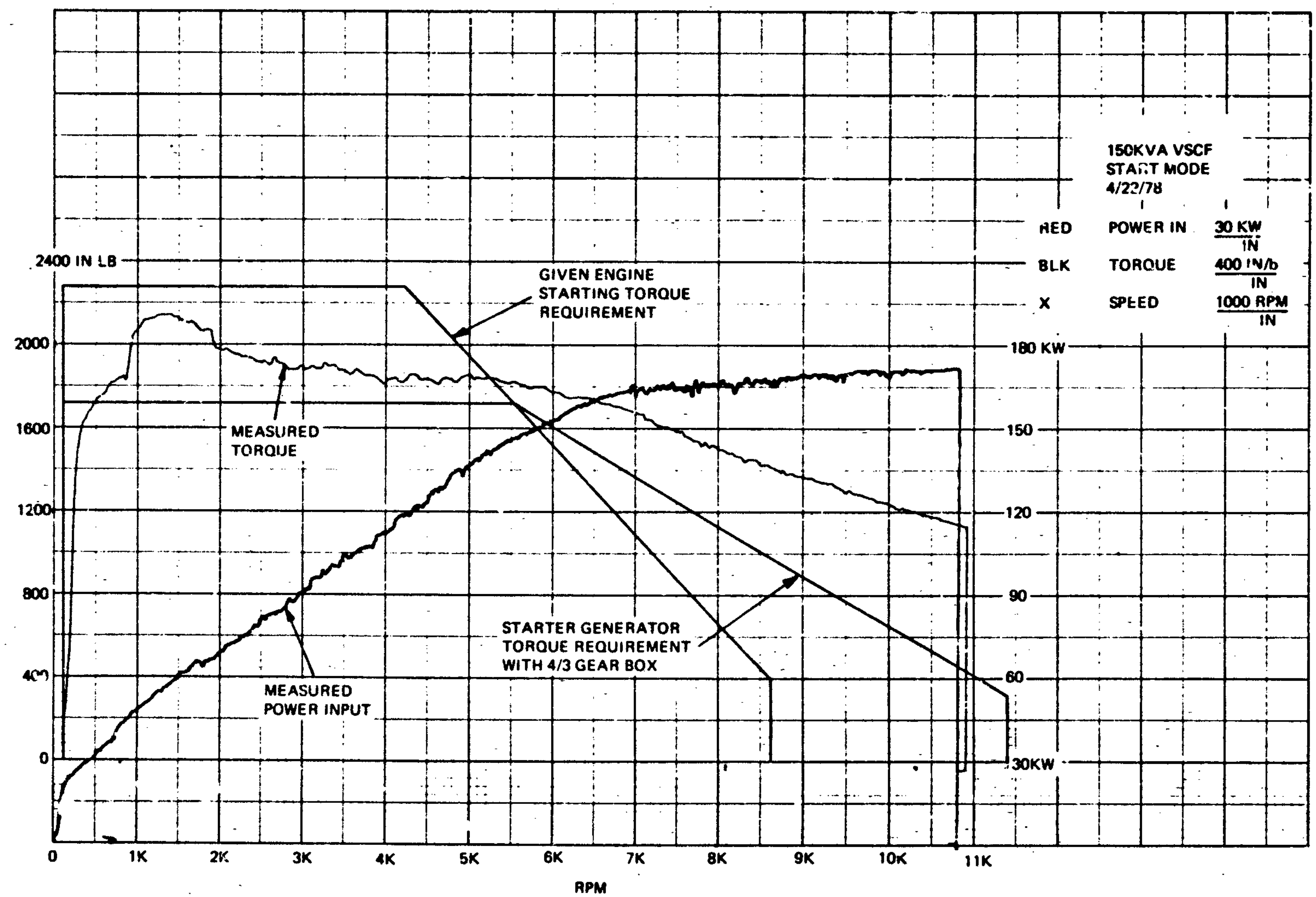


Figure 9. Start Mode Torque and Power

SECTION III

BACKGROUND

A variable speed constant frequency generator is a high speed, high frequency, synchronous machine. The normal generator design is composed of a main synchronous generator, an exciter, and a permanent magnet generator (PMG). The main generator is a wound rotor, salient pole, brushless machine whose output is fed into a static cycloconverter. The exciter is an inside out synchronous generator that supplies power through the rotating rectifiers to the main generator field. The PMG supplies excitation power for the exciter and power for the VSCF system control.

Permanent magnets have been utilized in rotating machinery in various manners such as the control power supply but have never been seriously considered as a replacement for high power wound rotor generators. Permanent magnets can be substituted in any type electrical machine where the magnetic field is produced by a direct current excitation as it is in the case of synchronous machines. Incorporating a permanent magnet concept into the VSCF generator will eliminate the need of the control PMG, the exciter and the rectifier system. Prior to the availability of samarium cobalt several characteristics of permanent magnets prevented their use in these applications. They exhibited a relatively low energy density and a comparatively poor resistance to accidental demagnetization.

The negative factors of permanent magnets have been eliminated with the advent of rare earth cobalt magnets. This type of magnet exhibits a demagnetization curve which is close to the ideal magnet curve and provides a high magnetic energy product in conjunction with a high coercive force. These characteristics permit the rotor design for synchronous machines to be optimized with respect to overall performance without the magnets being the limiting item. The result is that relatively small portions of the rotor volume are occupied by the magnets allowing a larger amount of volume to be utilized for mechanical support structure.

The key to a mechanically successful high speed permanent magnet generator as required in a VSCF system is the magnet containment. Various means are conceivable to cope with these kinds of forces. General Electric has successfully built numerous rotors using the shrink ring containment technique. A ring is shrunk over the magnet assembly to hold the magnets and pole pieces in place. At the speeds selected, the minimum shrink ring thickness (>0.2 inches) is large enough to interfere with the electromagnetics even with rare earth magnets as the source of excitation if the shrink ring is completely made out of non-magnetic material. (Magnetic material shrink ring would magnetically short the magnets.) Therefore, a shrink ring made from sections of non-magnetic and magnetic materials was fabricated. The weak point in such a shrink ring is the bond between the two dissimilar metals. The key to successful rotor design lies in the shrink ring manufacturing.

A further utilization of permanent magnets in synchronous machines is in a VSCF starter-generator application. It has been shown before by General Electric* that a VSCF generating system can be used in the reverse power flow mode to motor the rotating machine and start the aircraft engine. The more difficult portion of this approach is the requirement to produce high torque at zero speed. For a wound rotor system, excitation power must be transferred to the rotor at zero speed. This transfer has been done but requires a different, slightly larger exciter than necessary in the system used for generating only.

This problem of excitation at zero speed is non existent for a PMG since the excitation is built into the rotor with the magnets.

Two basic modes are available to operate a synchronous generator in the motoring mode. The simplest one is to operate the machine as a synchronous motor. In this case the only link between the rotor and the rotating magnetic field produced by the stator windings is through the electromagnetic forces. This link is of the spring type, which allows the rotor to change its position with respect to the rotating field as a function of the mechanical loading of the rotor shaft. This method of starting is relatively unstable.

By introducing an additional rotor position feedback which will control the stator input frequency, the instability will be eliminated. In addition, feedback allows precise control of the rotor position with respect to the rotating magnetic field and thus, precise output torque control. This feature can also be used similarly to the field weakening control for dc machines which results in a speed increase under constant input voltage.

In order to achieve the rotor position feedback, a rotor position sensor is incorporated in the machine. This sensor consists of 3 Hall Probes located 120 electrical rotor degrees apart. These probes are positioned to utilize the leakage flux at end of the rotor stack. With the Hall probe signal feedback the cycloconverter is used to program the position and frequency of the rotating magnetic field.

*Final Report, 60 KVA VSCF Converter Product Improvement Program February 16, 1973. U.S. Navy Contract No. N00421-72-C-6702 GE report number, DLL-730216.

SECTION IV
DESIGN

4.1 SYSTEM DESIGN

The system design follows closely the plan described in Section IV of the Phase I Report. The permanent magnet machine and cycloconverter combination are especially attractive as a starter generator since both components inherently allow reversal of power flow and because excitation for the machine is always present.

4.1.1 SYSTEM DESCRIPTION

Figure 10 is a block diagram of the system. At the center of the page is the main power path of the PMG, the converter-filter and the 400 Hz terminals. Power flows from right to left during the start. 400 Hz power is converted to 9 phase variable frequency, variable voltage, phased by the PMG rotor position. The PMG machine then converts this electrical power to mechanical power.

In the generate mode, nine phase variable frequency, variable voltage power from the PMG is converted to three phase 400 Hz power at 115 volts. The power circuit is the same in both modes. The signal level circuits control the firing of the SCR's in different patterns to achieve the change of mode.

4.1.2 POWER CIRCUIT

The basic power circuit is identical to that of the earlier Wound Rotor (WR) 150 KVA system. Each of the nine generator phases is connected to each of the three output phases through an SCR of each polarity. Current and power can flow either from machine to output or reverse. Figure 11 shows the generator and one output phase of the converter.

The SCR's are grouped in sets of three, which connect to a three phase machine winding. The sets are then paralleled by interphase transformers (IPT). These IPT's permit current flow in each SCR for 120 machine degrees and divide the total output phase current equally between three SCR's at any instant. If all rectifiers were tied together, the output current would flow in only one SCR at a time and for only 40°. The IPT, therefore, greatly eases the current requirements of the SCR's (and the generator). Equally important only 1/3 current must be switched or commutated from SCR to SCR at any instant.

4.1.2.1 SCR's

Neglecting the filter capacitor current, each SCR conducts 1/3 of the phase output current for 1/6 of the time (1/2 for each polarity times 1/3 for each machine phase). The approximate SCR current at rated 150 KVA 115V is $\frac{150,000}{3 \times 115} \times \frac{1}{3} \times \frac{1}{\sqrt{6}} = 59$ amps RMS. The SCR's used are selected from the Westinghouse T607 family; 235 amp stud mounted devices.

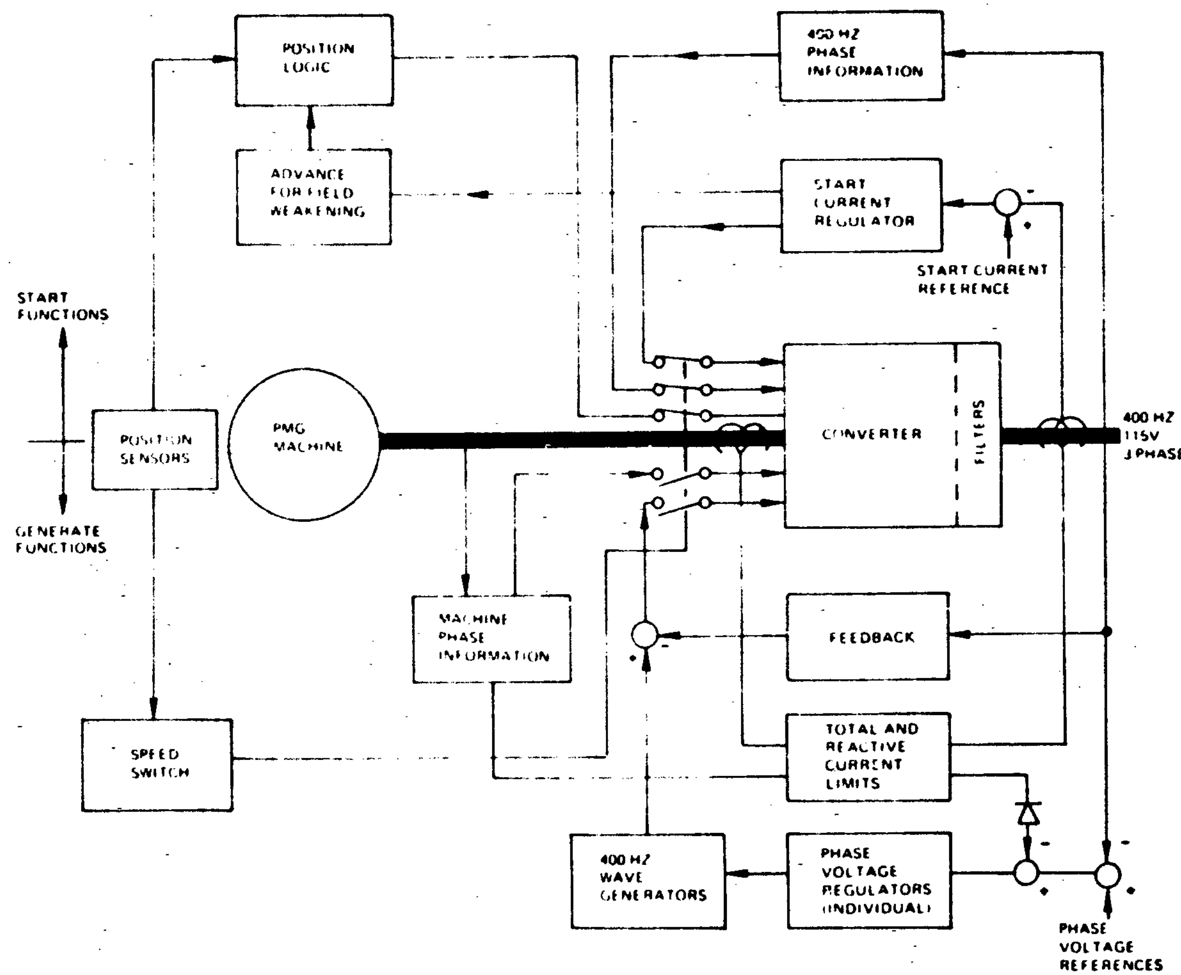


Figure 10 System Block Diagram

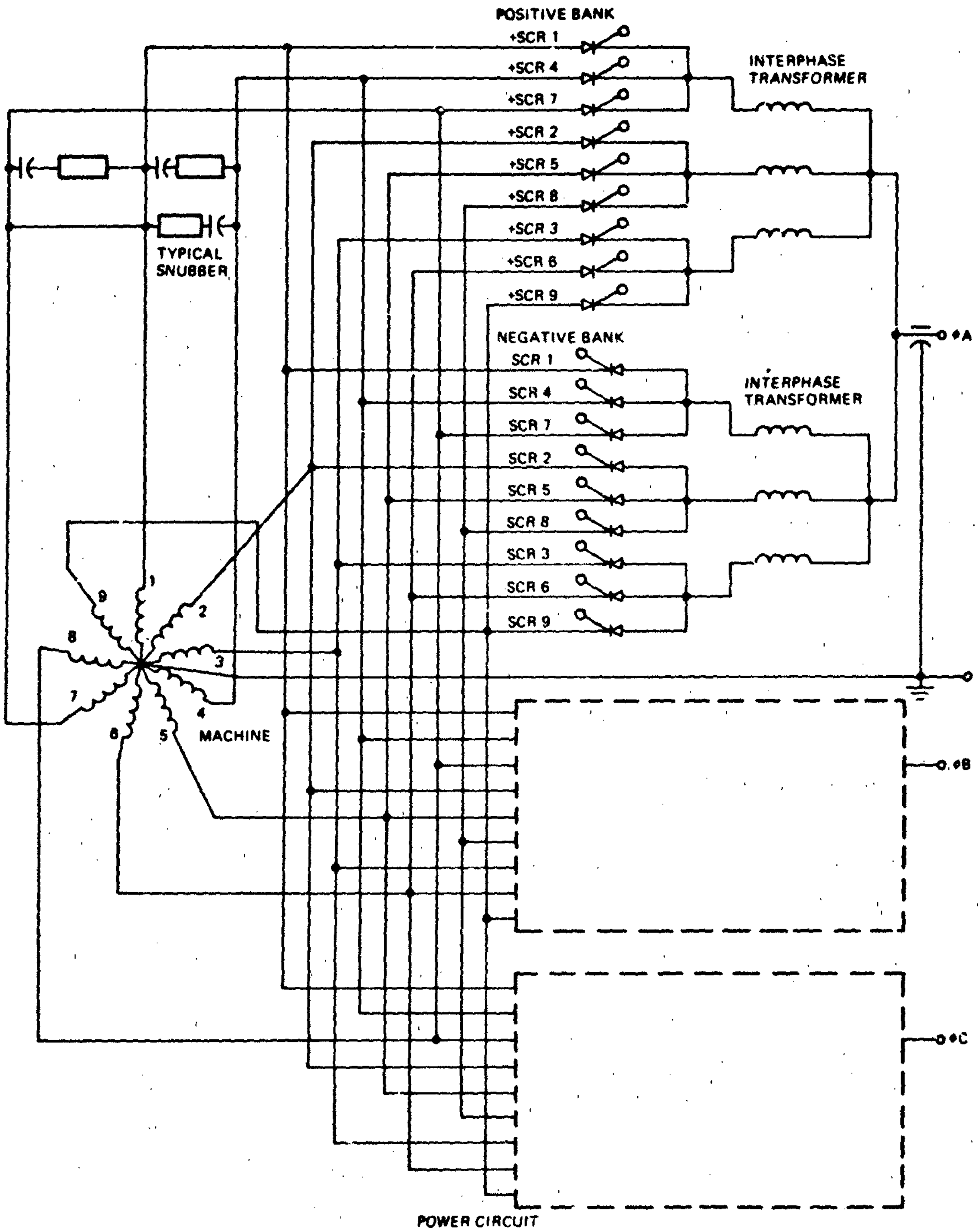


Figure 11. Power Circuit

Significant SCR specifications are steady state voltage 1200, transient voltage 1400V and 50µs turn off with 400V/µs re-applied voltage. As explained in paragraph 4.1 of the Phase I Report, peak SCR voltage was predicted at 1000V. 860 volts was the peak of the predicted generator three phase line to line voltage and commutation spikes of 140 volts were assumed. Actual voltages are considerably less because the generator voltage is about 10% less than predicted and because the transients at commutation are very low. Relatively slow SCR's may be used because the machine voltage rises with speed. At high speed where turn off times are most critical in conventional VSCF systems, the high machine voltage means the SCR's are phase controlled within a relatively narrow band about 90° so there is extra time from the latest SCR firing until line to line voltage reversal.

4.1.2.2 Snubber Circuit

Commutation in the cycloconverter takes place by gating of a new SCR which provides a more favorable current path than did the conducting SCR. Both SCR's conduct while the current decays in the old path which transiently short circuits the two generator phases. Current does not stop in the old path when it reaches zero because the SCR does not block inverse voltage until the minority carriers are swept out. The SCR currents as shown in Figure 12 have substantial reverse spikes. When the outgoing SCR does block, the voltage at the generator ends of the SCR's recovers to the generator voltage. All other SCR's connected to these generator phases experience this voltage change. Half of them see dv/dts in the direction to try to turn them on. The capacitor of the snubber limits the dv/dt and the resistor damps the LC oscillation to limit the peak voltage amplitude. The typical voltage transient is shown in Figure 13. The step is caused by the SCR recovery current transferring to the snubber. The rest of the transient is the damped LRC oscillation. Since the SCR recovery current is hard to define we make our preliminary snubber design assuming instantaneous SCR recovery. With wound rotor machines satisfactory results are obtained using machine inductance measured with a standard bridge. Snubber components of 20 ohms and .25ufd were selected which give idealized transients with about 15% overshoot and .4 times phase voltage dv/dt.

Testing with the PMG machine showed that the LRC circuit (composed of the machine subtransient inductance and the snubber RC) is overdamped. The machine voltage returns to its normal envelop after the commutation is completed. There is no overshoot such as is shown in Figure 13. The machines commutating inductance is not like the almost ideal inductor of the standard wound rotor machine. The commutating inductance is a resistance - inductance network which has high losses in the frequency spectrum of the sharp edges of the commutation. These losses are evidently caused by eddy currents in the solid rotor surface.

The snubber resistors were reduced to 9 ohms and the transient was still overdamped. This indicates a further reduction in resistor value is possible and this fine tuning would lower converter losses and component size. Part of this loss saving in the converter, however, is transfered to the machine.

Each of the nine 20 ohm snubber resistors in the original design was actually ten -200 ohm 50 watt resistors in parallel. Each of the nine 9 ohm resistors in the final configuration is actually eight 75 ohm 30 watt resistors in parallel

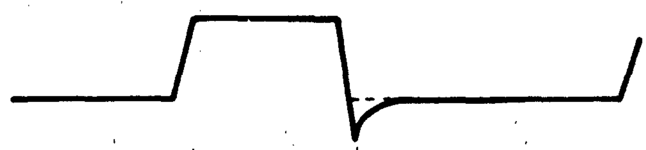


Figure 12. SCR Current

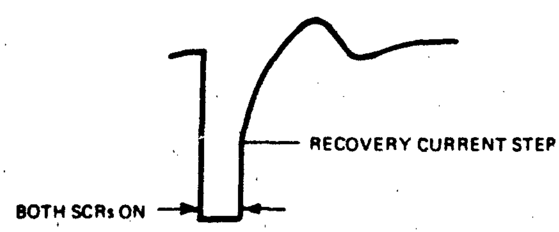


Figure 13. Typical Voltage Transient

4.1.2.3 Interphase Transformers and Filter Capacitor

The leakage inductance of the interphase transformers (IPT) and the capacitor at the phase terminal forms the filter which suppresses the rectifier ripple and higher harmonics of the output wave. With a nine phase machine and a base frequency of 1400Hz, the minimum rectifier ripple frequency is approximately 12kHz. The IPT leakage inductance is about 8 microhenries and the filter capacitor 600mfd. The other components of the filter which are less obvious are the three machine phases which are conducting at any time and the equivalent commutation resistor. The commutation resistor for a nine phase generator with 3 commutating groups is equal to the machine frequency times commutating inductance. This equivalent resistor has no power loss but nevertheless damps the LC output filter just like a real resistor.

The non-regulated output of the PMG make the requirements for the IPT much more severe than in the WR machine. At high speed, and/or light load, excess machine voltage is rejected by phasing the SCR's, on average, nearer 90°. This maintains the 400Hz output voltage but increases the rectifier ripple at each SCR bank. The IPT, which averages the three SCR banks, must absorb this voltage and increased core loss results.

The indicated IPT design is, therefore, one which has less iron and more copper than normal, and one with good heat flow paths from the iron.

Another area in the IPT design where improvement over the earlier WR 150 KVA system is desirable is containment of leakage flux. In that IPT, Figure 14, 400 Hz leakage flux comes out the end of the IPT and acts as an induction heater for any aluminum chassis in the vicinity.

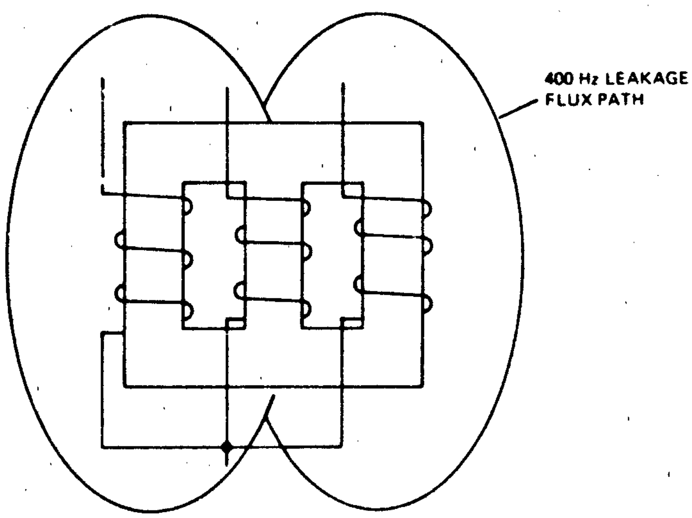


Figure 14. Three Leg IPT

In the selected IPT arrangement shown in Figure 15, each functional IPT is actually three devices. This scheme lends itself to a copper heavy design, gives multiple short heat flow paths from the cores, and by arranging the windings as shown, minimizes the stray flux problem. The obvious disadvantage is that there are more devices to make, mount, and interconnect.

The filter capacitor duty is increased but not to the same degree. The major change is that the ripple current remains constant with machine speed rather than decreasing as the machine speed goes up as occurs with a regulated WR machine system. 600mfd of capacitance is used in the PMG design compared with 540mfd in the earlier WR system.

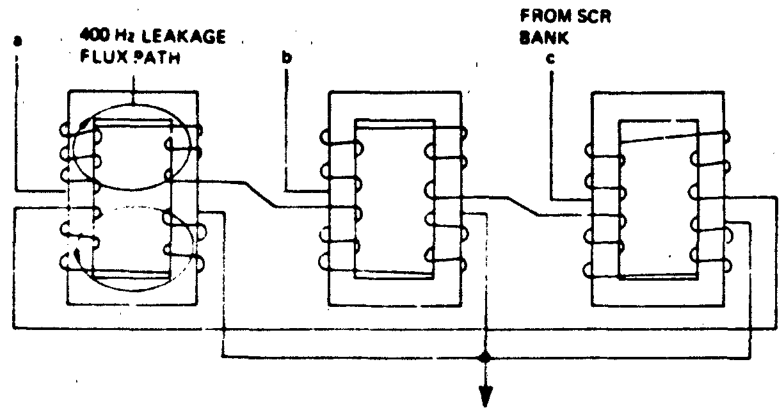


Figure 15. Equivalent Three Leg IPT by Combining Three Two Leg IPTs

4.1.3 GENERATE MODE CONTROL FUNCTIONS

4.1.3.1 Reference Wave Generator

The VSCF system in generate mode is basically three high power amplifiers which reproduce three low level 400Hz reference waves at 115V and at the power level required by the load. The reference wave generator develops the three phase set of 400Hz waves which are to be amplified. These reference waves have less than 1% total harmonics, are very accurately spaced 120° apart and are individually amplitude controlled. A secondary function is to generate 400Hz square waves which serve as discriminator references for the load division circuits.

The reference waves are generated by digital logic circuits which function as micropower pulse width modulation inverters. The principal ripple frequency is above 70KHz so that only a very small RC filter is required to smooth the 400Hz wave. Amplitude control is accomplished by clipping the digital pulses so that the reference wave amplitude, when amplified by the converter, satisfies the phase voltage regulator.

4.1.3.2 Frequency Control

The system is designed for parallel operation. It must be able to change frequency to synchronize with the system to which it is to be paralleled. The chosen paralleling method is that of averaging the frequency references of the paralleled channels to establish the system frequency. The primary reference is a crystal oscillator. The secondary reference is a voltage controlled oscillator (VCO) which drives the wave generator. The frequency control operates by counting the beat frequency between the crystal and voltage controlled oscillators, determining which oscillator frequency is higher and converting the result into an analog voltage. This analog voltage is compared with synchronization and load division signals to set the frequency of the VCO and therefore of the system. This technique permits very high gains so that op amp offsets and other temperature and component shifts have little effect. With the 3MHz frequency of the VCO, it is easy to make the frequency control loop response fast enough so it has a negligible effect on the stability of the load division loops.

4.1.3.3 Phase Voltage Regulators

The phase voltage regulators compare the converter output voltages sensed at the point of regulation with a DC voltage reference and adjust the reference wave amplitudes to regulate the converter output. The regulators sense the rectified average of the output rather than the RMS value. The converter output voltage measured by RMS meters varies slightly with load and speed even though the regulator does an almost perfect job of holding average voltage. This variation is due to change of waveshape. Experience has shown the regulation to be satisfactory even after allowing for waveshape effects so the added cost of true RMS sensing is not justified.

The phase regulators become current regulators when the system output is shorted or overloaded. When the output current exceeds the set limit, the current path, which has very high gain overrides the voltage sensing regulator. If there is a short circuit, the voltage sense and comparison circuits are saturated. By making the voltage path saturation levels different for the three phases, the current regulator is phase sequential in the event of multiple phase faults. For example, with a three phase to ground fault, full fault current is delivered on Phase A and low currents by Phase B and C. This will trip a three phase breaker just as fast as full current in all phases. With indiviaual breakers, Phase A breaker will be tripped first and then full fault current will be delivered to B. When B breaker opens fault current will go to C.

This technique minimizes heating in generator and converter and torque required by the machine.

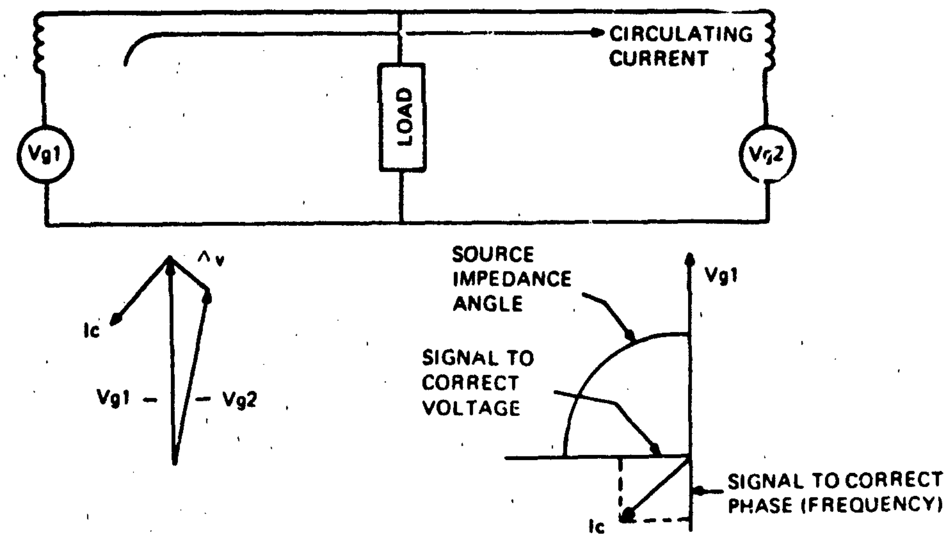
Each phase regulator also has an input from the load division circuits to force load sharing during parallel operation. This input is described in detail in the load division section.

The final input to the phase voltage regulator comes from the beta circuit. This signal can act only to reduce system output. It comes into action during startup, when a miscommutation has been detected, or when large reactive loads are applied to the system.

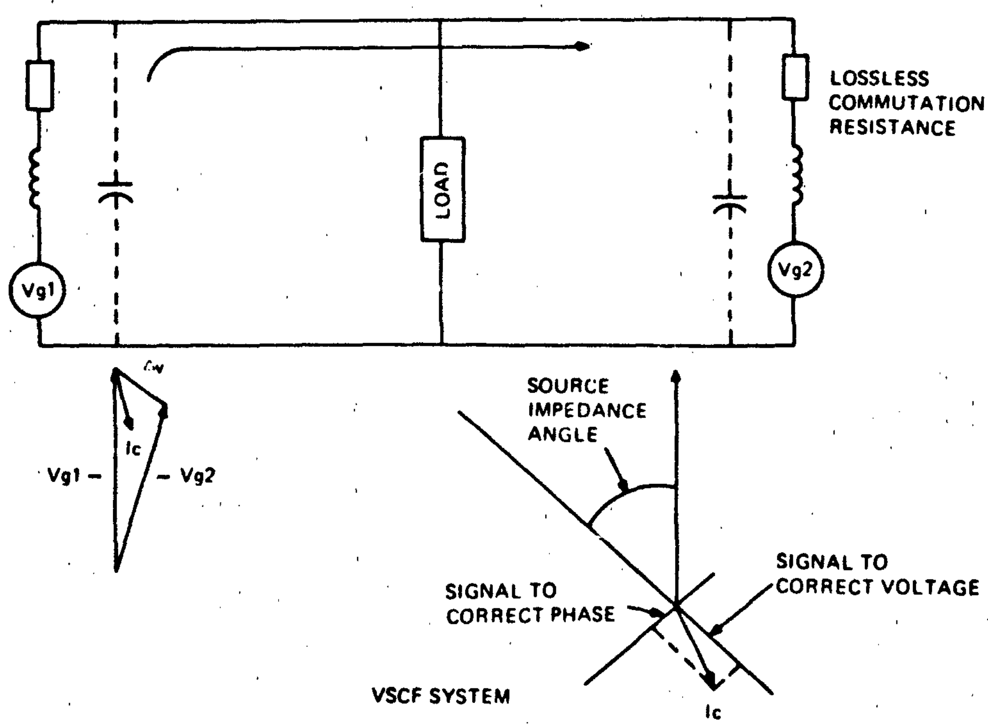
4.1.3.4 Load Division

Parallel operation of VSCF systems is somewhat different from that of synchronous machines although the fundamental rules apply. With synchronous machines operating in parallel, the circulating current in phase with the voltage provides the signal to control the speed of the prime movers or the phase of the generated voltage. The circulating current at right angle to the voltage provides the signal to control the voltage regulators. The reason for this is shown in Figure 16 phasor diagrams. The source impedance of the synchronous machine is largely inductive. Circulating current therefore lags the phasor difference of generated voltage by about 90°.

The source impedance of a cycloconverter is made up of the shunt filter capacitor, the leakage inductance of the interphase transformer, the sub-transient reactance of the machine, and a lossless resistance resulting from commutation. The commutation resistor is equal to the machine commutating inductance (12ph) times the number of phases in a commutating group (3) divided by the number of commutating groups in parallel (3) times the machine frequency (1400 - 2450Hz). The commutating resistor of the 150 KVA PMG system varies from .017 ohms at base speed to .029 ohms at top speed. The source impedance angle at 400Hz therefore varies from about 60° inductive at base speed to about 46° at top speed. The load division circuits which bias the phase regulators must sense the component of circulating current at about 50-55 degrees lagging with respect to the



SYNCHRONOUS MACHINE SYSTEM



VSCF SYSTEM

Figure 16. Derivation of Load Sharing Signals for Parallel Systems

terminal voltage. The phase or frequency bias circuit senses current at right angles to the source impedance angle or 35-40^{o} leading the terminal voltage.

The circulating current is measured by current transformer loops which compare the phase currents of the two systems. Phase discriminators then measure the components of this current as described above. The references for these phase discriminators are derived in the reference wave generator.

Before paralleling, the two systems are brought into synchronism by phase discriminators which look at the system terminal voltages.

4.1.3.5 Modulators

The modulators determine the exact firing time for each SCR. In the generate mode, the SCR's are controlled by what is normally called the biased cosine method. It is more accurate to describe it as the integral of the commutated voltage method. This integral becomes a cosine wave only when the power source is sinusoidal and has very low impedance.

Figure 17 shows the operation of the modulator in the generate mode. The SCR firing can be controlled over a 180^{o} interval and the modulator is inhibited for the second 180^{o} interval. The modulator delivers a train of pulses starting at the firing angle and ending at the inhibit interval. Normally only the first gate pulse is relevant because it triggers the SCR into conduction. The following train of pulses is added for insurance in case the SCR did not fire on the first pulse. The first gate pulse sometimes fails to latch in the SCR, because commutations in other output phases have temporarily suppressed the generatior phase voltage connected to the SCR.

A train of pulses rather than a solid pulse allows the pulse transformer size to be greatly reduced which in turn simplifies the design of the transformer for very fast rise time.

Figure 18 is a typical modulator circuit. Comparitor AR1 with direct positive and lagged negative feedback is a gated oscillator. Transistor Q1 is a buffer and level shifter. Since it is never saturated, it has very good switching characteristics. Q2 is the drive transistor for the pulse transformer. Fast turnoff is insured by diode CR1 and reverse breakdown of Q1 emitter to base when comparitor AR1 is negative. The gate pulse is made to approximate a current source by the resistor in series with the transformer primary.

The oscillator is gated into action when logic gate U1 is high. In the generate mode, this occurs when the comparitor AR2 which compares a firing wave and the error goes low and when the blanking wave is low. The third input is always low in the generate mode. The blanking wave goes high during the inhibit half cycle to stop the oscillator.

In the start mode, the comparitor output is held at Logic 0 when 1 for generate is low. The other two inputs are from the start current control and from the rotor position logic that replaces the blanking wave. These signals will be discussed further in the description of the start mode functions.

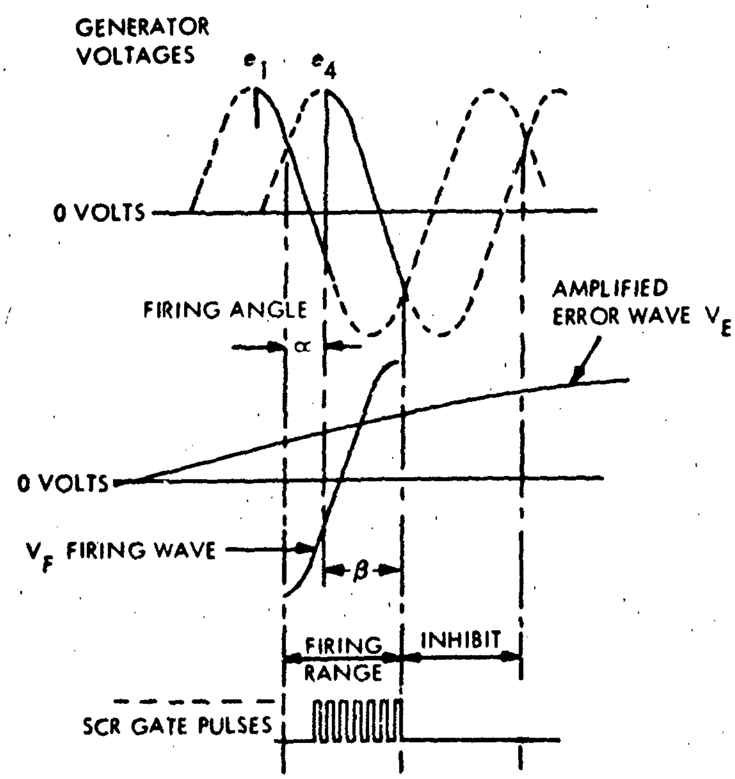


Figure 17. Waveforms Illustrating the Generation of the SCR Gate Pulses

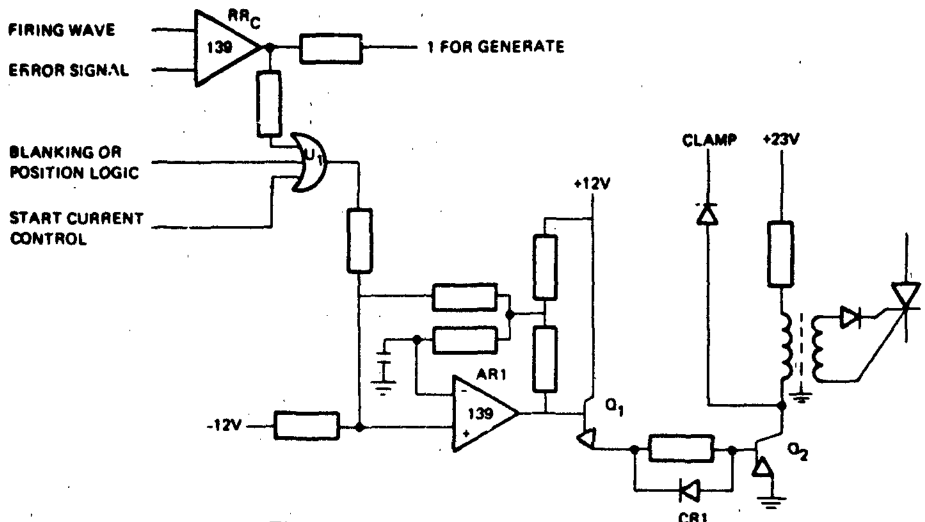
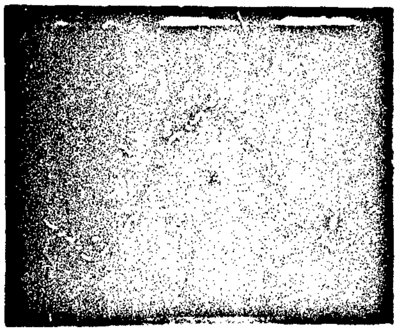


Figure 18. Modulator Circuit

4.1.3.6 Firing and Blanking Wave Circuits

As noted in the modulator description, the basic SCR control is by the biased cosine method. In 60Hz rectifier systems, the cosine firing waves are usually obtained by a phase shifting transformer connected to the incoming utility power. In VSCF systems, the generator waveshape is not usually a very good sine wave since it is usually possible to obtain slightly more power from a given machine size if its waveshape is not restricted. The machine impedance is also significant as the photograph Figure 19 shows. Each SCR commutation adds a substantial notch or pedestal to the wave.



BASE SPEED
.1 MS/CM
200 V/CM
150KVA @ .95

Figure 19. Generator LINE-LINE Voltage

It is, therefore, necessary to go back to the basic operation of a phase controlled rectifier to derive suitable firing waves. Figure 20 shows the fundamental circuit of an SCR commutating off another SCR. AC voltage source e_1 is conducting and source e_4 is to be switched in. These represent two phases of an AC machine with L_c being the commutating inductance or approximately the machine subtransient reactance divided by 2π times frequency.

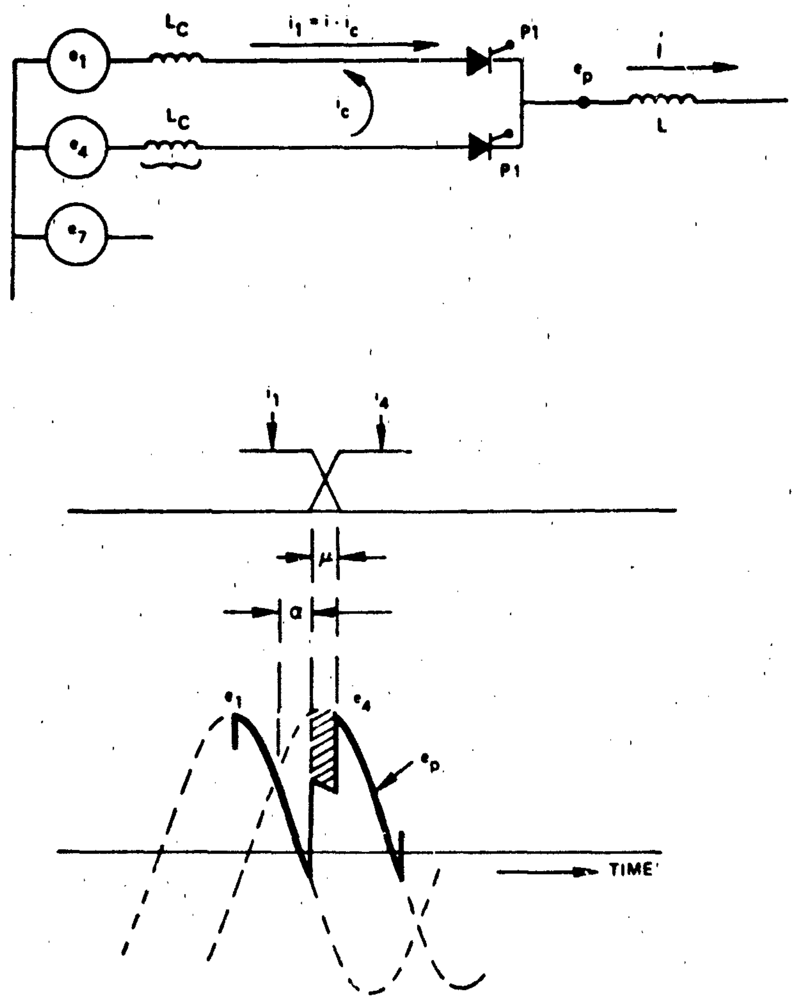


Figure 20. Commutation

The voltage reduction as the result of phase retard and commutation is

$$\int (e_1 - e_4) + \int L_c \frac{di}{dt} = \int (e_1 - e_4) + L_c i$$

$L_c i$ is a linear term so that if the control function is the integral of the generated line to line voltage, the rectifier transfer function is a linear gain and a source impedance.

Since the generated voltages are internal to the machine, they cannot be used to derive the control function directly. Terminal voltages and phase currents are used, as Figure 21 shows, to derive the firing waves for each set of 120° displaced machine phases.

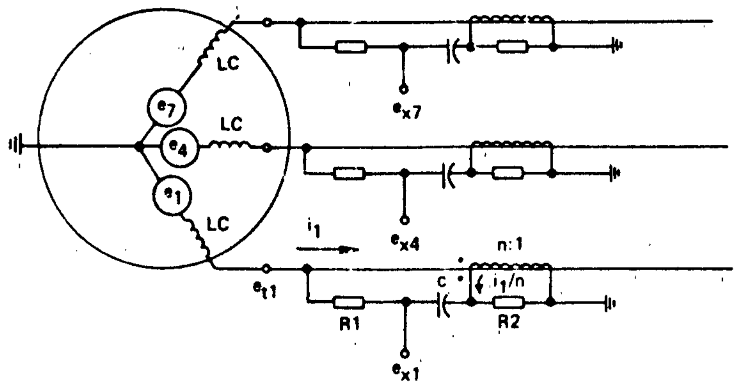


Figure 21. Circuit for Deriving Firing Waves

One of the required firing waves is:

$$e_{fw} = \int (e_1 - e_4)dt = \int e_1 dt - \int e_4 dt$$

But,

$$e_1 = e_{t1} + L_c \frac{di_1}{dt}$$

$$\therefore \int e_1 = \int e_{t1} dt + L_c i_1$$

If $R_1 C >> \frac{1}{f_{gen}}$, then

$$e_{x1} \approx \frac{1}{R_1 C} \int e_{t1} dt + \frac{R_2}{n} i_1$$

$$\text{or} \quad e_x \approx \frac{1}{R_1 C} \left[\int e_{t1} dt + \frac{R_1 R_2 C}{n} i_1 \right]$$

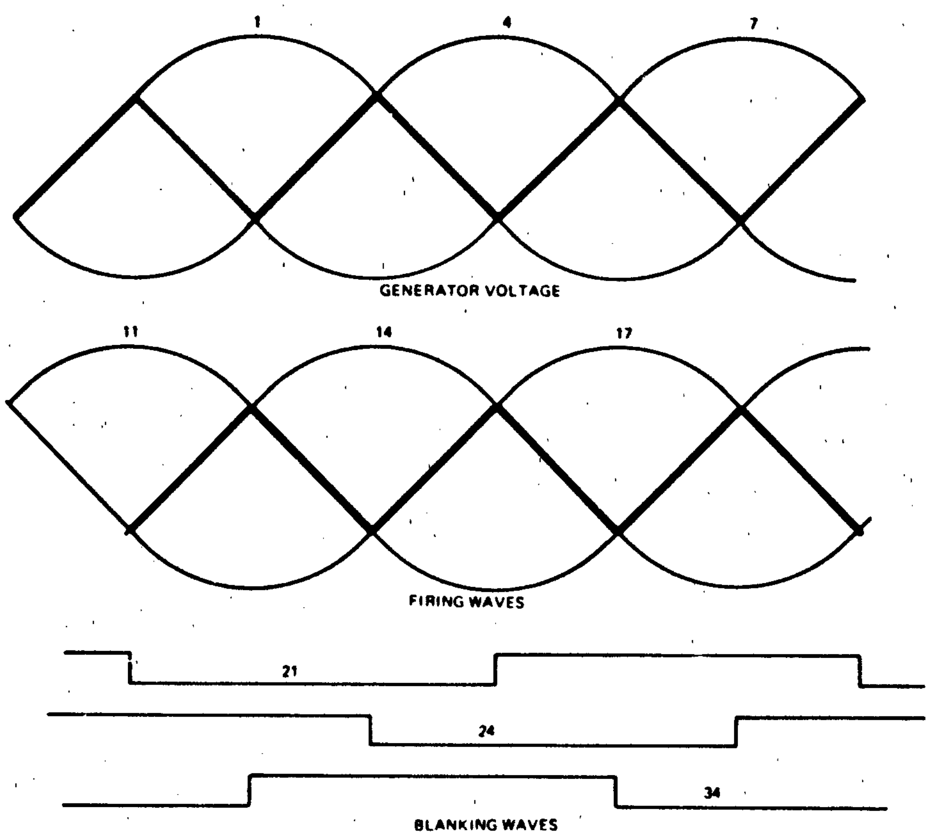


Figure 22. Machine Voltage, Firing and Blanking Waves

The terms in the brackets are identical with the right side of equation (A-12) when R_1R_2 C/n is scaled to equal L_c. Thus, e_{x1}, e_{x4} and e_{x7} are the required firing waves when connected line-to-line. The blanking or inhibit waves, which restrict the gating pulses to the half cycle when positive voltage is applied each SCR, are derived from the firing waves rather than directly from the terminal voltages. This is fundamentally correct since the firing waves represent the generated voltage. Figure 22 shows a set of machine voltages, firing waves, and blanking waves for the idealized sine wave case. Comparitors whose inputs are connected to firing waves derive the blanking waves. The blanking waves are fed to the modulators via tri-state CMOS logic gates. When in start mode, these gates are in the disabled or open circuit state.

Firing and blanking waves also go to the beta circuit where they are used to establish the sampling periods for generator current representing short SCR turnoff margins.

4.1.3.7 Mixer

The mixer circuit sums the 400Hz reference signal and several feedback signals to develop the error voltage which goes to the modulator.

Figure 23 shows the signals of the mixer circuit. Feedback block G2 has very high low frequency gain to suppress the DC voltage level of the output to a few millivolts. Block G3 senses the voltage at the rectifier banks and is used to improve waveshape and to reduce the converter source impedance thereby minimizing the voltage transients during load switching. This path has moderate gain at 400Hz.

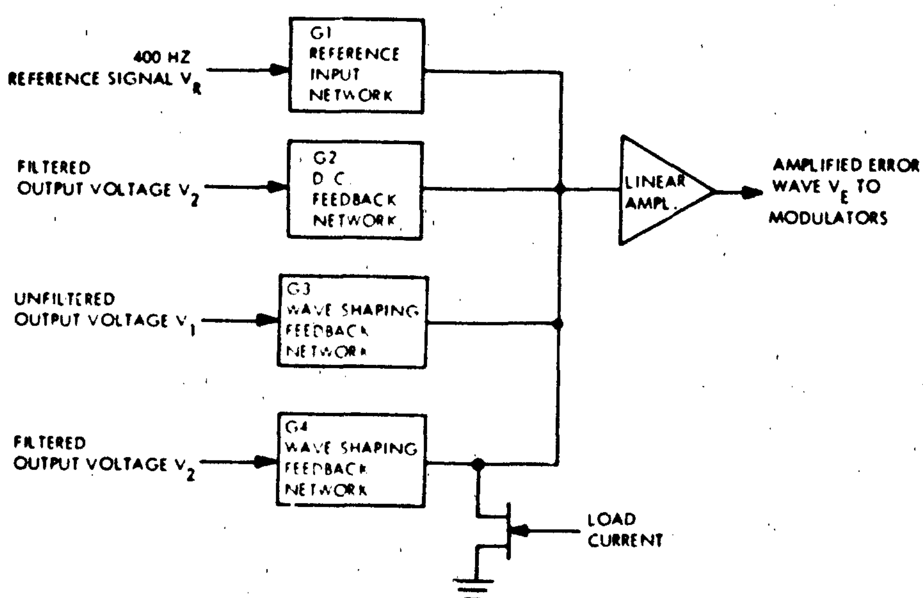


Figure 23. Components of the Mixer Amplifier

Block 4 feedback is used for waveshaping to suppress the lower harmonics of the 400Hz output. It therefore has highest gain in the harmonic frequency region. During severe overloads or short circuits, this path tends to cause miscommutations. Most of this signal is therefore shunted to ground by a Field Effect Transistor acting as a variable resistor when the output current is above its rated load level.

The mixer also adds offset bias to the error voltage so that the output wave generated by the negative SCR's is more positive than the wave generated by the positive SCR's. This offset, or safety margin bias, generates a DC voltage which opposes current flow from positive SCR's directly back through the negative SCR's shown in Figure 24.

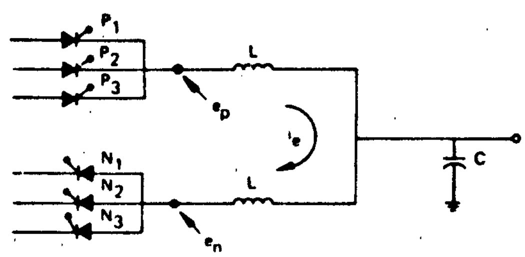


Figure 24. Circuit for Equalizing Current

4.1.3.8 Beta Circuits

Beta, in a phase controlled rectifier, is the angle from the firing of the SCR until the line to line voltage reversal of the supply phases connected to the conducting SCR and the SCR being triggered. The time represented by this angle must be sufficient to complete the comutation and for the SCR to recover its voltage blocking ability. The function of the beta circuit is to detect current in the machine phases when it occurs at an angle where little time margin is left to complete the commutation and allow the SCR to regain its blocking ability. This function is mechanized by sampling the currents of three generator phases. The sampling period is established by the firing and blanking waves and a reference much the same way as a normal SCR firing instant is set.

When current in this region is detected, signals are sent to the phase voltage regulators to depress the output voltages. Reducing the output voltages then reduces the output current and also reduces the maximum SCR phase retard. Normally the beta circuit is exercised only transiently when very large reactive loads are applied. Examples are starting of large motors and the magnetizing current inrush of large transformers.

In most VSCF systems, the beta is most needed at high speed where the shorter cycle period results in minimum SCR turn-off time. With a PMG system, the increase of machine voltage with speed results in narrowing the band of SCR firing points. SCR recovery time is therefore maintained or increased as the speed raises. The limiting condition with the PMG system is at heavy load, base speed where machine voltage is minimum.

The secondary functions of the beta circuit are startup and miscommutation detection. Before startup, the beta circuit is maximum which fully clamps the phase voltage regulators and therefore the wave generators. When the logic signals that the system is to start, the beta circuit output decays and the clamp of the phase voltage regulators is released. This allows the converter to build up smoothly to 115V. At system shutdown, the phase

voltage regulator is again clamped. It takes a few milliseconds for the modulator supply to discharge so the converter outputs are programmed down before the last SCR fires. This minimizes the voltage present on the large output filter capacitor when all power circuits are opened.

Miscommutations are detected by comparing the generator current with the output current plus a bias. When operation is normal, the sum of the generator currents is equal the sum of the output currents plus the filter capacitor currents. The filter capacitor fundamental currents are essentially constant since the output voltage is constant.

Therefore, when the sum of generator currents exceeds the sum of output currents plus a suitable bias, current must be flowing from some generator phases and back through others without going out through the load or filter capacitor. This is exactly what happens during miscommutation. When a miscommutation is detected, the phase voltage regulators are clamp which results in all SCR's being phased to about 90^{0}. If the miscommutation was not caused by a component failure, the system will recover and normal operation is resumed.

4.1.3.9 Logic and Protection

The VSCF system is a complete generating system. It has the logic required to start up and switch automatically into parallel. It contains protective circuits which shut off the converter if power quality is abnormal which protects the load equipment. It also has protective circuits to limit damage to the system in event of failure.

During normal operation, the system either starts up automatically when the generator comes up to minimum speed or manually by operation of the channel control switch. Power quality is then checked before the power ready latch is set (Figure 25). The logic then checks to see if automatic paralleling is required and if so are the conditions for paralleling satisfied. The line contactor is then closed provided the contactor switch is closed.

The bus tie contactor is normally closed except when the bus tie switch is open. Closure to the switch causes immediate closure of the contactor unless both systems are on line. In this case, contactor closure must wait until the autoparallel circuit determines that the two systems are in phase.

If the opposite system is on line, the newly started system automatically synchronizes with it.

The two major types of protection circuits are power quality protections and damage limiting protections. The power quality protections insure that the load equipment will not be damaged or malfunction because the generating system is not functioning properly. These protections are:

Overvoltage

The overvoltage circuit senses each output phase. If any or all phases exceed 123.5 volts, the system is de-energized for a time period inversely proportional to the overvoltage. If the system is in paralled a bias from the load division circuits is added to or subtracted from to the sensed overvoltage. If the load division signal is trying to decrease the regulated voltage, this system is probably the cause of the overvoltage so the bias speeds up the trip. If the load division is trying to increase the regulated voltage, the cause of the overvoltage is probably in the other system so the bias slows down the trip. This feature allows selectively tripping off only the failed system.

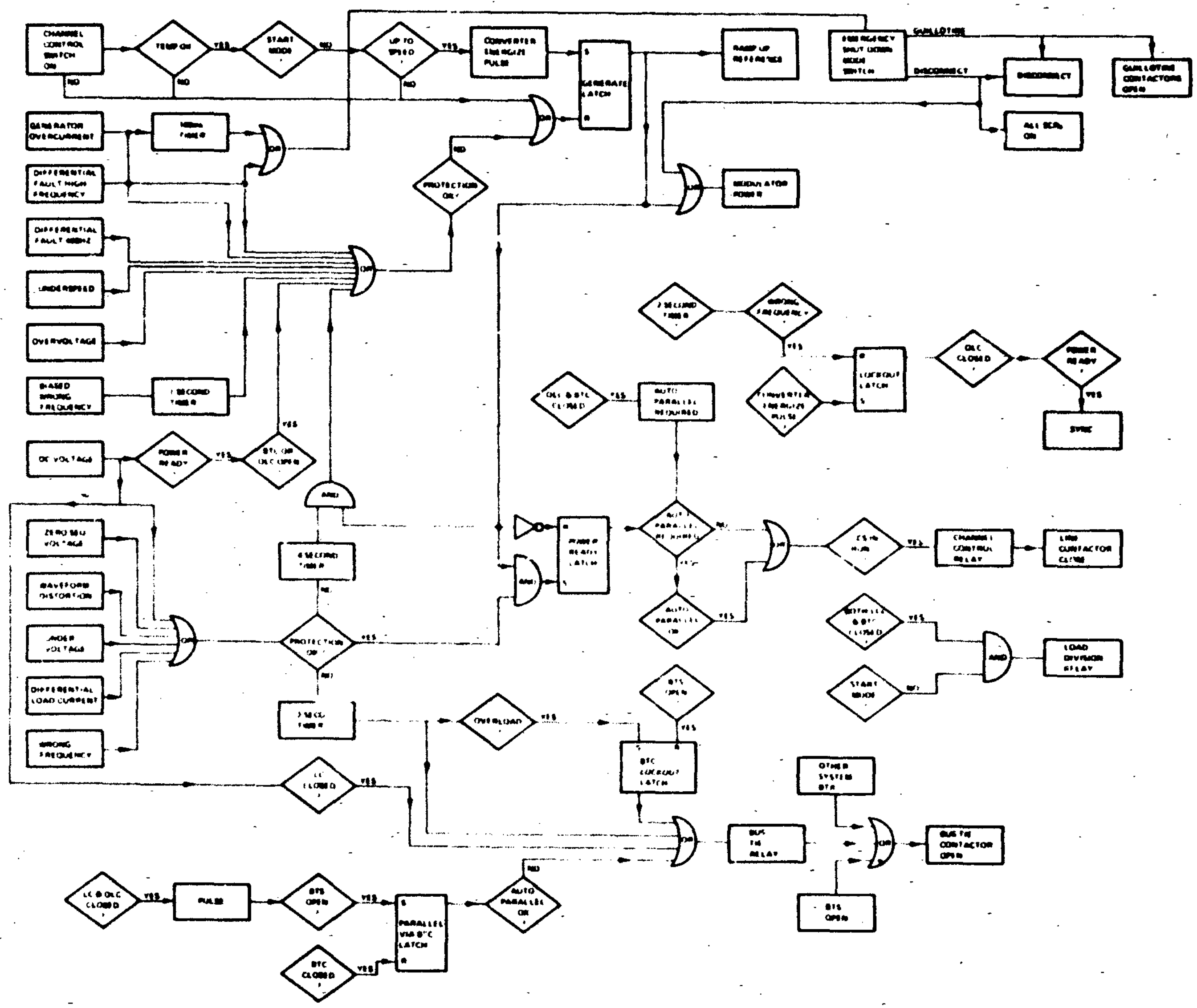


Figure 25. Generate Mode Logic Flow Chart

DC Voltage Protection

This is a protection function particular to VSCF systems and is required because certain failure modes can result in large DC voltages in the output. Ultimate trip is below 0.5 volts. Trips with larger DC content have trip time inversely proportional to amplitude of the DC so the integral of voltage above .5 is less than .5 volt seconds.

Wrong Frequency

If the system goes outside the band of 386 to 413Hz for one second, the system is tripped off. If the load division circuitry is biasing the frequency in the direction that it is out of limits, the trip is inhibited for four seconds since the probable failure is in the other system.

Undervoltage

If any output phase is below 104 volts for four seconds the system is tripped. The bus tie contactor is opened after two seconds and is locked open if overload current existed at this instant. If there were no overload, the tie contactor would reclose when the undervoltage cleared or when the faulty system tripped.

Waveform Distortion

If any output phase wave is seriously distorted, the system is tripped in four seconds. The bus tie contactor sequence described above occurs.

Zero Sequence Voltage

The system trips in four seconds if the zero sequence voltage exceeds 3.5 volts. The bus tie contactor again opens in two seconds.

The damage limiting protection functions are:

Differential Fault - 400Hz

This function protects the 400Hz feeders from the converter to the line contactor. Faults are sensed by a current transformer loop. Trip is immediate if a fault is sensed.

Differential Fault - High Frequency

This function covers the machine and the high frequency transmission lines protection. Current transformers in the machine neutrals and in the converter cover this zone. Since the machine is a PMG, the normal procedure of de-energizing the machine is impossible. Two modes of shutdown in this emergency are provided. The first method is to open the high frequency line contactors and actuate the machine's mechanical disconnect. If the fault is in the high frequency feeders on the converter side of the contractors, this de-energizes the fault. If

the fault is in the machine or machine side feeders, this does not clear the fault. Actuation of the disconnect stops mechanical power flow so the fault current will stop after the inertial energy of the rotor is dissipated. Machine damage may be extensive with this method.

The alternate shutdown method is to actuate the disconnect but leave the high frequency contactors closed and turn on all the converter SCR's. This multiple short on the machine is calculated to stop rotation in about one second from top speed of 21,000 RPM. Rotational energy is spread among all the machine windings, the transmission line, all SCR's and all IPT's rather than being concentrated in the actual faulted circuit.

While the concept of deliberately causing a massive fault is at first alarming, this technique looks best in the long range. Even at top speed the rotational energy, when spread around, can be readily handled. For example, with the prototype system, the SCR's and their heat sink will be heated by less than $5^{\circ}C$ during the braking. The machine windings have been calculated to rise at $100^{\circ}C$/second during the shutdown so only a slight loss of insulation life occurs.

Generator Overcurrent

This protection is for failures within the converter and are detected by comparing the total converter input and output current. Possible faults here include shorts of power circuits, SCR's, and faults which cause loss of control of the SCR's. The first reaction to this type fault is to shutdown the converter. If the fault resulted from a control circuit failure, machine current will stop when the SCR gating stops. If the generator overcurrent continues after converter shutdown, one of the alternate emergency shutdown methods described above is initiated.

Three other protection circuits are included which do not fall in the two main types.

Underspeed

This is a condition for operation rather than an actual protection. The underspeed circuit inhibits operation in the generate mode at low speed. Hysteresis is included to avoid cycling if the input speed wanders about the pickup point.

Differential Load Current

This circuit is protection against failure of the load division circuits when operating in parallel. If the two systems are delivering unequal current of more than the set level, the bus tie contactor is opened after two seconds.

Auto Parallel

This is another conditional function which allows initiation of paralleling only when the systems are synchronized and have approximately equal phase voltages.

4.1.4 START MODE

In the start mode, the system is the equivalent of a brushless DC machine supplied from a phase controlled rectifier. This analogy is shown in Figure 26. The converter provides the current control function by phasing the SCR's with respect to the incoming 400Hz power. The commutator function of switching current between the armature windings is provided by gating the SCR's as a function of rotor position. The PMG machine's field cannot be directly controlled since it is set by the magnets. The effective field can be varied however by adjusting the reactive current flow in the armature. Note that in a conventional DC machine or its brushless analogy there is no DC current or voltage in the armature except at standstill.

Field weakening at higher speeds is accomplished by phase advancing commutation with respect to rotor position.

In the start mode no attempt is made to apply sinusoidal voltages to the machine. This would be possible only at very low speed where the machine frequency is low compared with the 400Hz supply. The voltages actually applied to the machine are quasisquare waves which have 120° constant amplitude positive and negative periods with 60° zero voltage intervals in between. The neutral of the machine is disconnected from ground during the start so that the applied voltage is that of a six pulse rectifier rather than three pulse.

It was learned in the testing that best results are obtained if the neutrals of the three phase winding sets are isolated. A three pole contactor was therefore used for opening the neutral in start mode.

The required functions for the start mode are position logic which allows gating of SCR's as a function of rotor position, current control which phases the SCR's with respect to the 400Hz supply, and protection and switching logic.

4.1.4.1 Position Logic

The position logic and SCR's are the equivalent of the commutator of a standard DC machine. The position logic selects which SCR's to fire allowing current to flow in the stator phase windings. For optimum torque, current should be 180° out of phase with the machine generated voltage. This is possible only at low speeds where commutation is by the supply. At higher speeds the current must be switched earlier as shown in Figure 27, to allow the machine to do the commutation.

The position logic sets 18-120 machine degree intervals where sets of SCR's can be gated. There is a 120° interval for each polarity of each phase.

The sensors which actually report rotor position are Hall probes sensing the leakage flux at the end of the rotor. For ideal tracking of the rotor nine Hall probes are required. Actually only three were used. With only three probes, positions represented by the other six phases must be derived. One obvious possibility is to consider the outputs of the Hall probes as a micropower three phase generator and develop the intermediate angles by phasor addition. For reasonable accuracy, the outputs of all three probes must be equal which requires the gain of the probes be matched or their excitation be individually adjusted. The method used is a phaselock loop with a nine stage ring counter to derive the nine phase positions. The loop includes three phase discriminators comparing the three probe outputs and three of the counter stages.

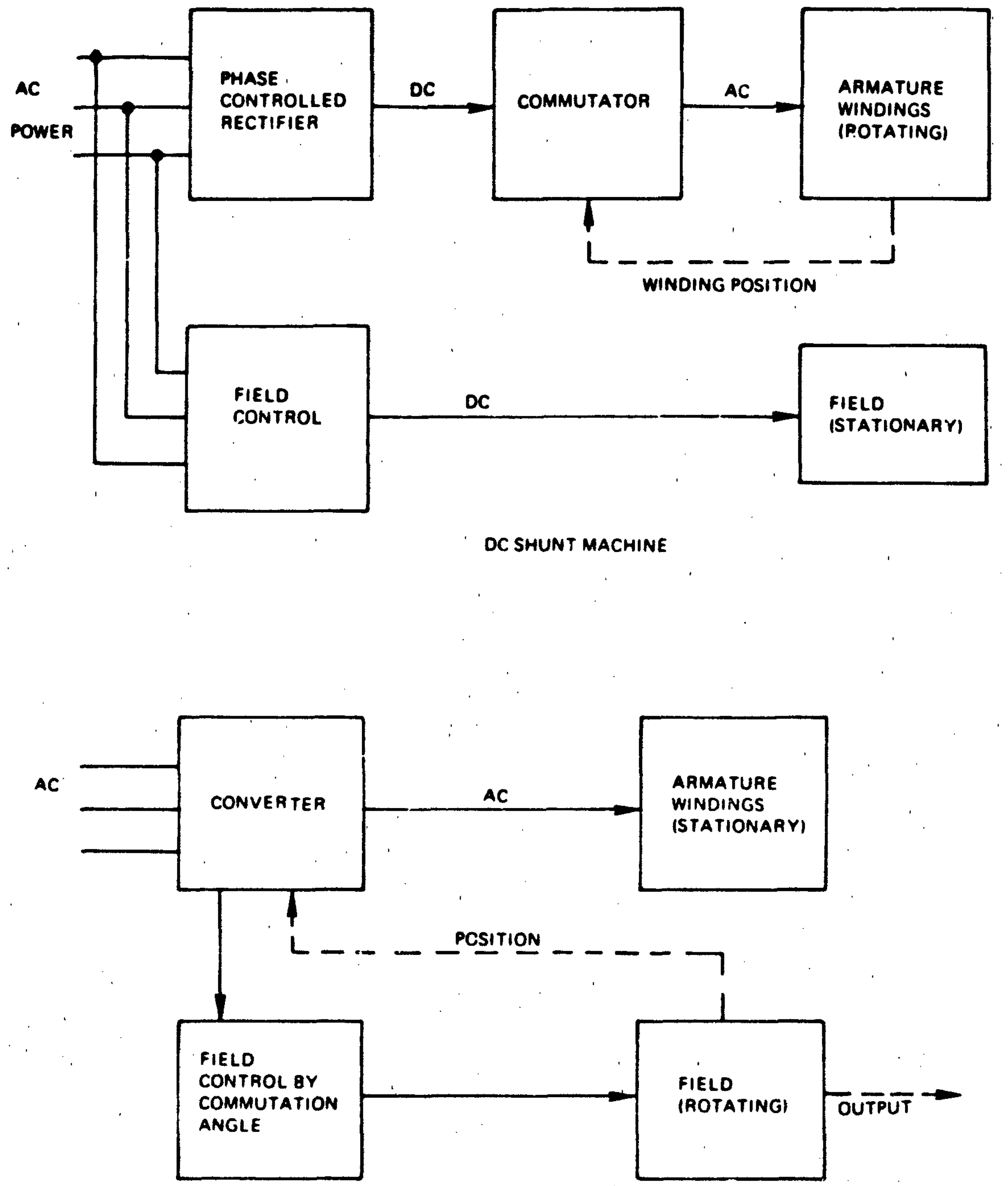


Figure 26. DC Machine Analogy in Start Mode

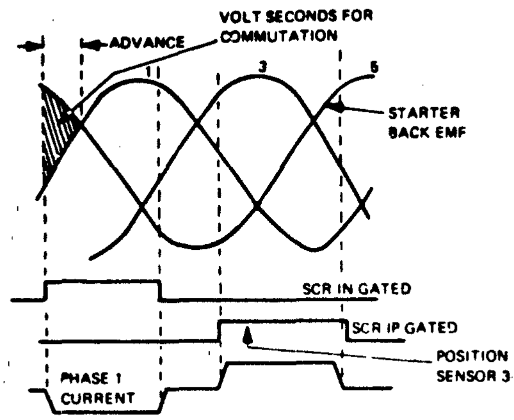


Figure 27. Phase Advance for Commutation

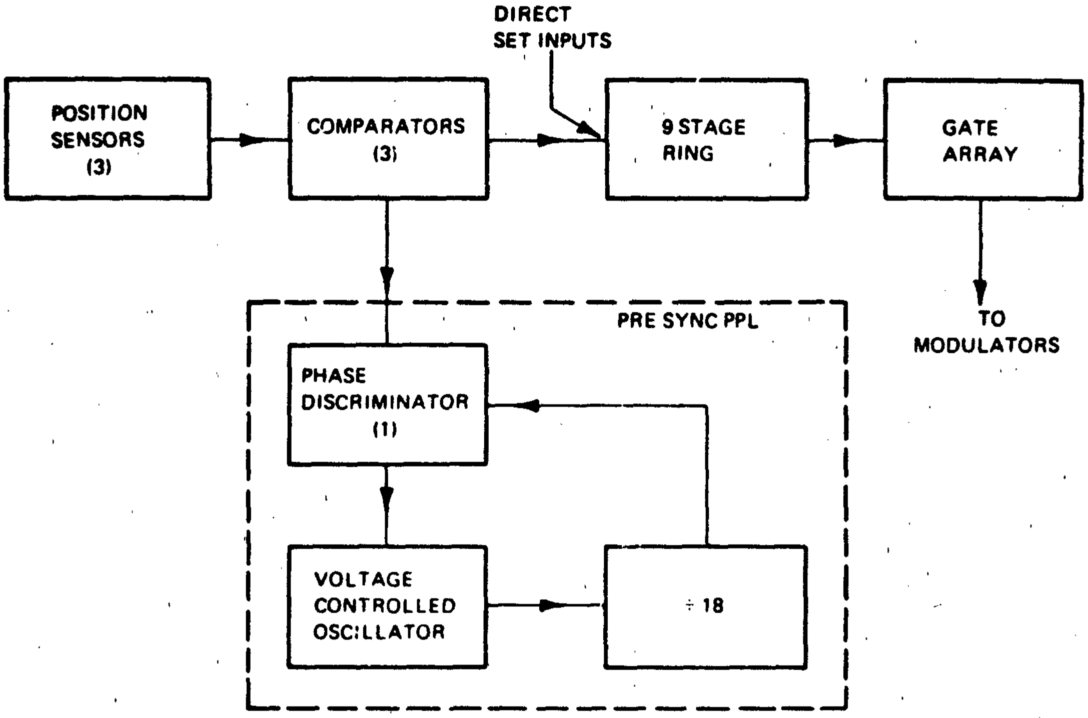
Use of the phaselock loop has several advantages. First, of course, is that it derives the intermediate phase angles. Second, it averages the three probe outputs. Since each electrical degree represents 7 mechanical degrees in a 14 pole machine, accurate placement of the probes is difficult. Finally it is easy to electrically shift the phaselock loop to change the angle of SCR switching. Ability to shift phase over a substantial angle is essential to get optimum torque, commutation, and field weakening.

The major problem with the phaselock loop is that it falls apart at very low speed and certainly at standstill. The solution was to use direct position sensing at low speed where commutation by the input 400Hz power is always possible and shift to the phaselock loop at 50-70Hz. This leaves the problem of what to do about the inbetween phases at low speed. The circuit was designed for two possibilities. The conservative circuit was the phasor addition method described. The simpler but more risky approach was to switch the SCR's as though the machine had only three phases in the low speed region. For example the positive conduction period of Phase 1 and the negative conduction periods of phase 5 and 6 are made to coincide. Phases 2 and 3 positive are made to coincide with 7 negative etc. No current is more than 20° away from optimum and since torque is proportional to the cosine of the angle between generated voltage and applied current, the maximum 20° position error gives cos 20° = .94 relative torque. The position error does not hinder commutation at low speeds where commutation is caused by the supply voltage and not by the machine voltage.

This method proved to be satisfactory.

Figures 28 and 29 show the block diagram of the position logic circuitry and the outputs in the two modes of operation. In the low speed mode, the comparitors directly set the ring stages. At a selected speed, the direct sets are disabled and the phase lock loop goes into operation. A pre-sync loop controls the VCO frequency during the low speed operation to minimize the transient at mode change.

Up to 200Hz, machine speed commutation by the 400Hz is always possible logic so the position logic is inphase with the machine voltage for optimum torque. Beginning at 200Hz machine voltage sometimes does the commutation and at 400Hz and above, the machine voltage does all the commutation. The position logic must advance the SCR gating to insure commutation as shown in Figure 27. This is done by shifting the phase lock loop with a signal proportional to speed.



POSITION LOGIC BLOCK DIAGRAM 3 PHASE MODE

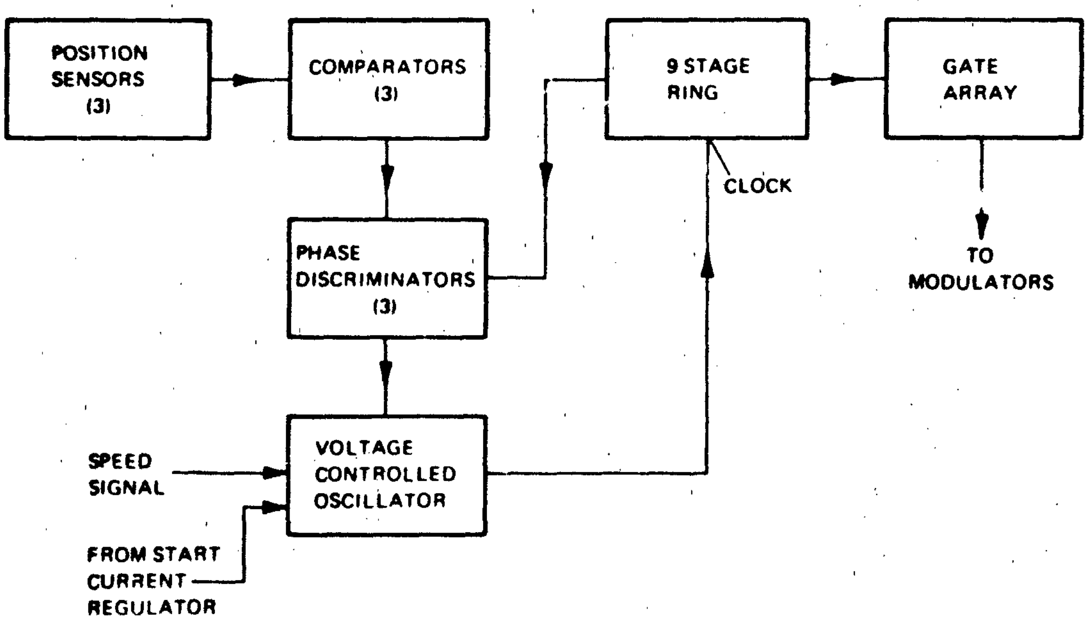


Figure 28. Position Logic Block Diagram 9 Phase Mode

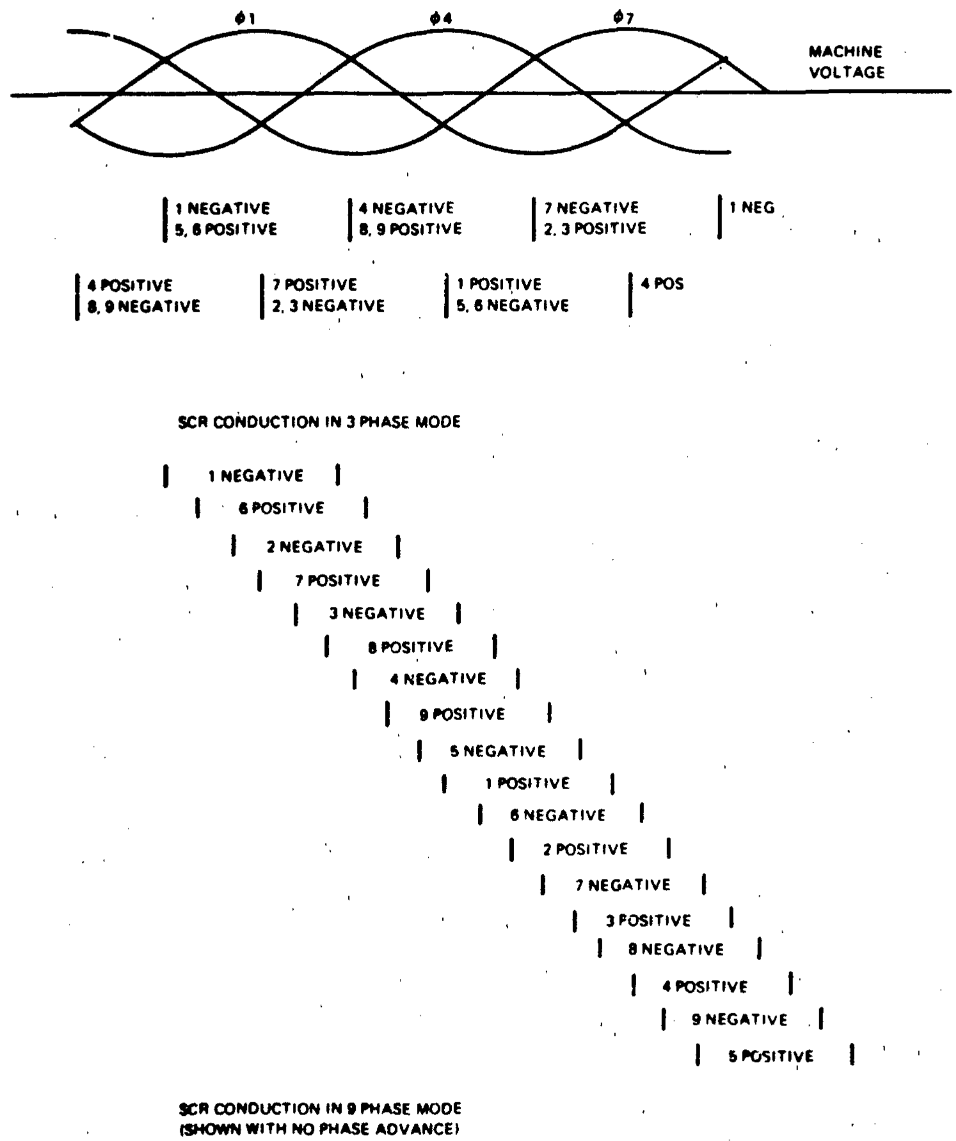


Figure 29. SCR Conduction in 9 Phase Mode (Shown With No Phase Advance)

Near the end of the start the machine voltage approaches the supply voltage. Current and torque would then decay. To maintain torque, the machine field must be weakened so high currents continue to flow into the machine. This is accomplished by further phase advancing the phase lock loop. This shifts the angle of the current applied to the machine so that more of the reactive component flows which demagnetizes the machine.

Some torque is lost because the current angle is less optimum. This new shift is initiated when the normal current regulator saturates. The amount of shift is controlled to maintain the desired current level.

4.1.4.2 Start Current Control

The start current control regulates the level of 400Hz current flowing into the system during the start. The rectified 400Hz phase currents are compared with a DC reference and the SCR's are phase controlled with respect to either the 400Hz input or rotor position.

At the beginning of the start the control mode is phase control with respect to the 400Hz. The biased cosine method of phase control described previously in the generate mode is used. The difference is that the firing and blanking waves are derived from the 400Hz input rather than from the machine. The start begins with the SCR's fully phase retarded. The slow regulator then phase advances the SCR's until the current satisfies the loop. Since balanced input current is desired, all SCR's are equally phase advanced. The SCR's to actually be fired are determined by the position logic.

As the machine speed increases, the generated voltage increases and the SCR's must be phase advanced to maintain the input current. At about 6000 RPM, the machine voltage has increased to the point where the SCR's are phased full on with respect to the 400Hz input. Input current and torque then drop rapidly unless the machine voltage can be reduced. As previously noted, the field of a PMG machine must be weakened indirectly by increasing the reactive component of current. This is done by advancing the rotor position phase lock loop.

This change of mode takes place automatically. When the current regulator amplifier voltage exceeds the peak of the firing wave, the 400Hz phase control loop is effectively opened so the regulator amplifier heads for saturation. Before it reaches saturation however, the regulator voltage breaks over a zener diode connecting it with the position logic. This now causes the input current to be regulated by controlling the machine voltage indirectly via reactive current.

The 400Hz control is de-activated when in the generate mode by tristate logic gates.

4.1.4.3 Start Mode Control Logic

Figure 30 shows a logic flow chart of the start operation. A momentary start switch sets the start latch provided the engine switch is on. The generate mode is inhibited and the machine neutral contactor opens. The 400Hz line contactor is closed and if voltage is sensed the start cycle begins.

A normal start proceeds until start cutout speed of 10,500 RPM is achieved. The start can be discontinued at any time by opening the engine switch. In the event of malfunction indicated by an overcurrent the start is automatically aborted. This overcurrent protection acts if the incoming 400Hz current significantly exceeds the normal regulated value for more than a few milliseconds.

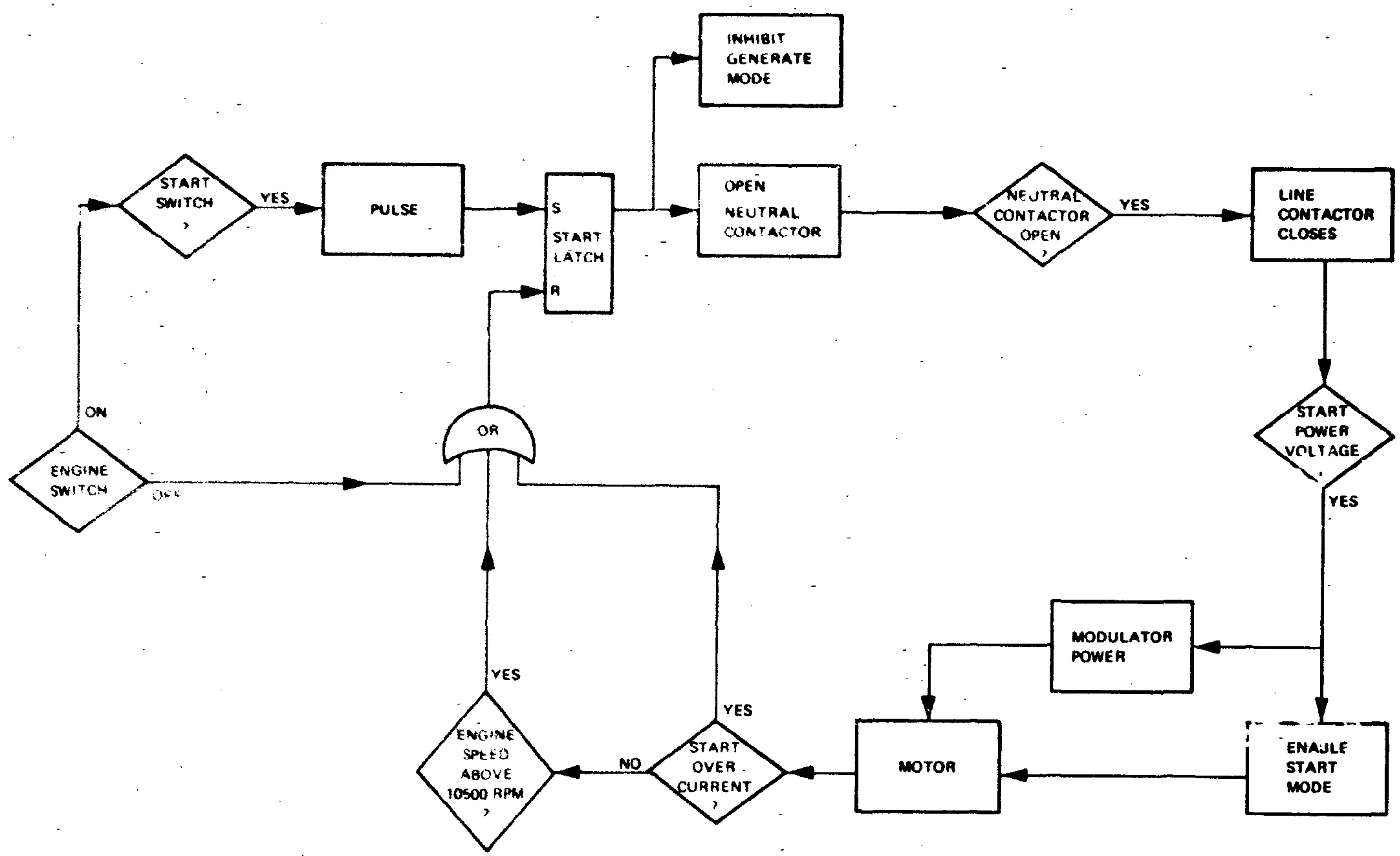


Figure 30. Engine Start Logic Flow Chart

When the start is terminated for any reason, the 400Hz line contactor is opened, the neutral contactor closes, and generate mode logic is enabled.

4.2 STARTER/GENERATOR DESCRIPTION

The starter/generator developed for this contract is an integral package which includes a 150 KVA variable speed constant frequency permanent magnet generator, with starting capability through the use of the generator windings, and a self-contained lubricating and cooling oil flow/pump. An outline of the generator package, depicting general configuration and interface locations is shown in Figure 31.

A general description of the configuration, function of the starter generator-gearbox major components, and the salient features and characteristics are provided in the following sections so that the merits of the equipment delivered may be better understood.

4.2.1 STARTER/GENERATOR

The starter-generator is a permanent magnet type machine with a nine phase output winding and a permanent field provided by rare earth magnets that are contained in an all-metallic rotor.

The starting capability is provided by application of power from the converter to the generator output windings. The generator therefore operates as a brushless dc motor. Sensors are used to detect angular relationship between the rotor poles and phase windings, functioning as the commutator, such that power is applied to the proper phase to produce torque for engine starting.

The generated voltage and power output to the converter is a function of speed. Therefore, the generator was designed for capability to deliver rated load and meet overload requirements at the 12,000 rpm base speed. At higher speeds the generator has the capability of delivering power exceeding specification requirements. As an example, the generator at the top operating speed of 21,000 rpm will deliver 1-3/4 the KVA output at base speed since the voltage increases proportional to speed.

This starter/generator design is considered inherently more reliable than conventional wound rotor type ac generators since the generator does not contain rotating windings, eliminates use of rotating rectifiers, has but one output winding, and is simplified by using substantially fewer parts.

A layout/cross-section view of the generator, with identification of components as referenced and described herein, is shown in Figure 32.

4.2.1.1 Functional Description

The function and construction of the starter/generator is presented by description of the major components, referenced in Figure 32 by component name, as follows:

4.2.1.1.1 Rotor

The rotor is a 14-pole ring segment design with seven 1.0 inch long ring segments. Each segment is constructed to contain the permanent magnets and the metallic members and to provide the required magnet path and mechanical strength. The ring segments are aligned and assembled on the shaft to complete the rotor structure.

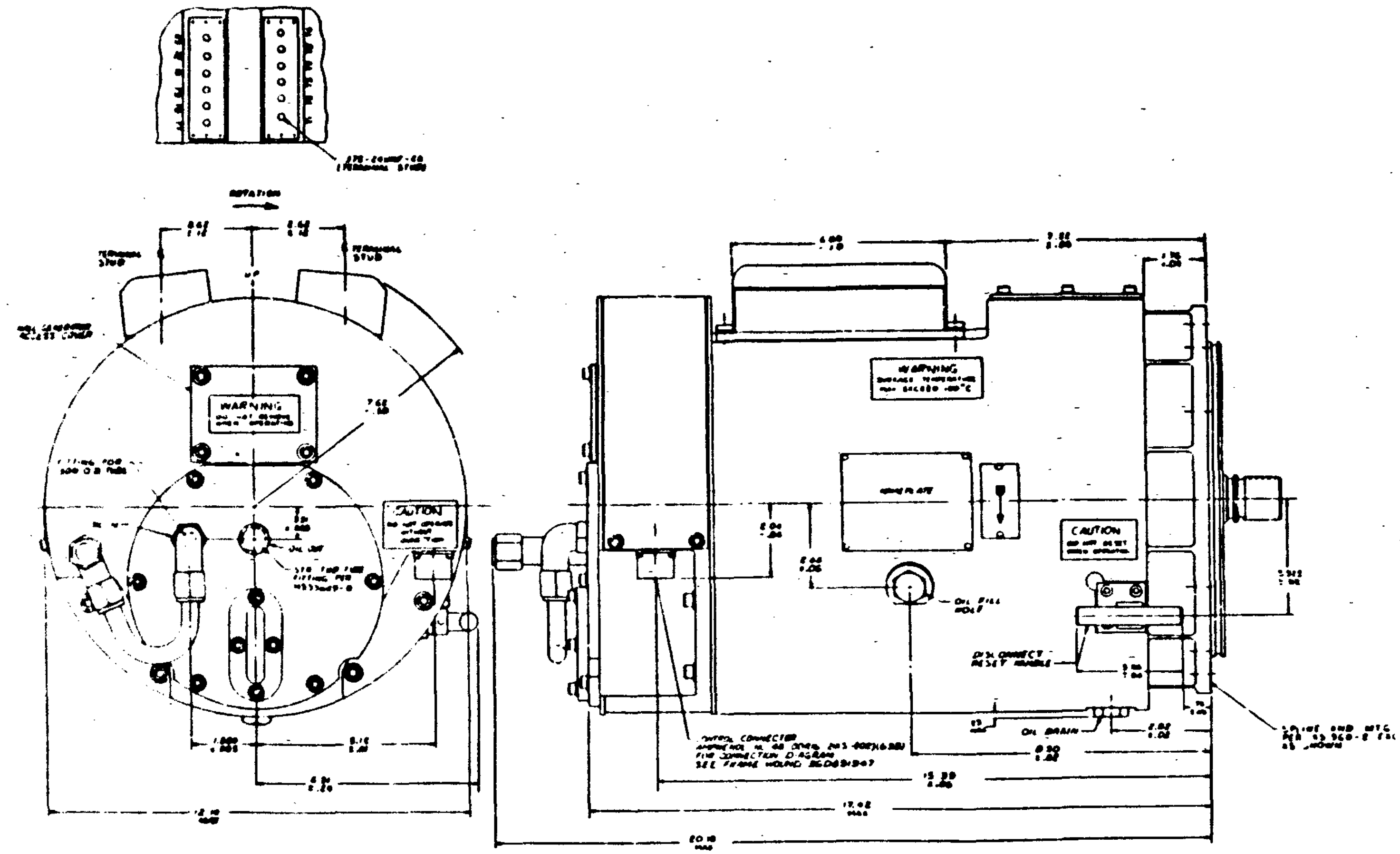


Figure 31. Generator Outline

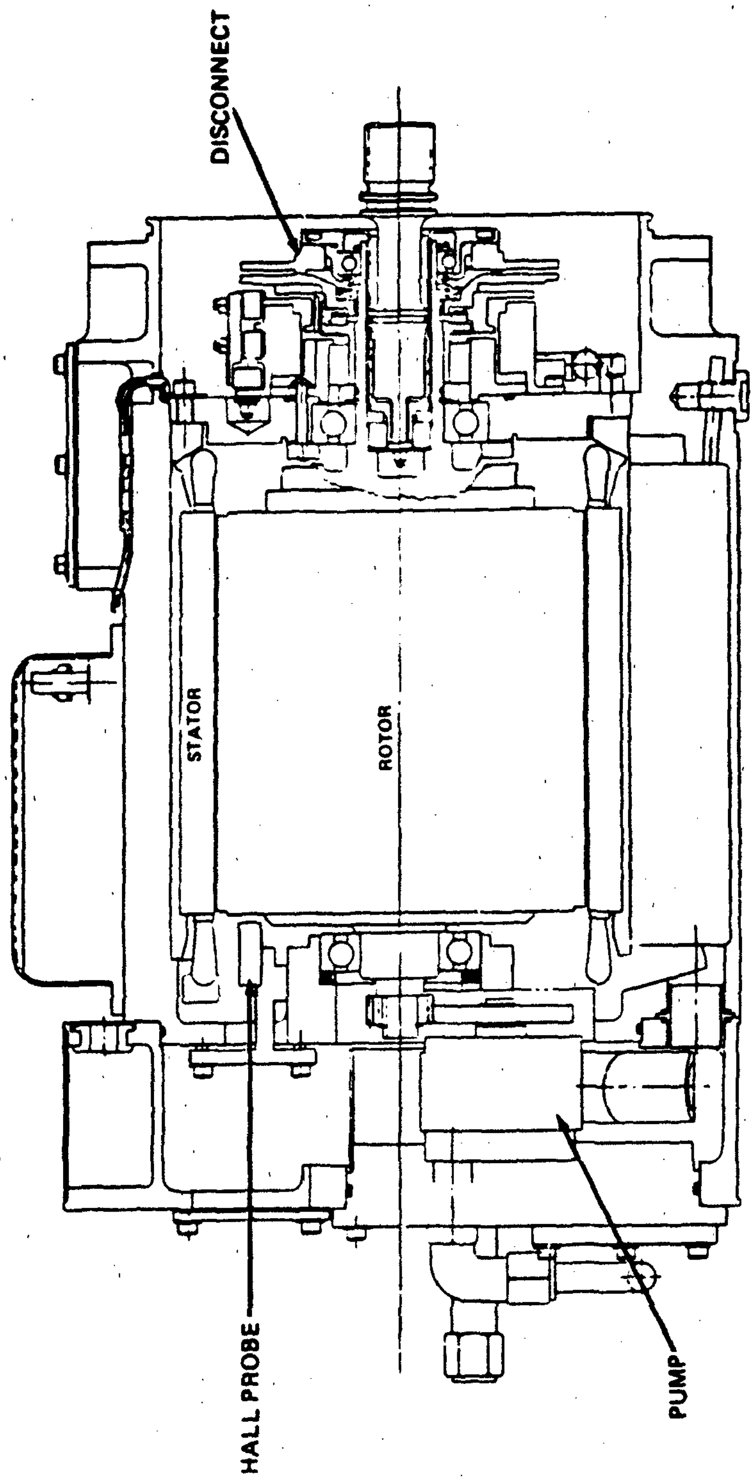


Figure 32. Generator Cross Section

A radial cross-sectional view of the rotor, with component names, is shown in Figure 33 as an aid to understand the material and construction which is described by component as follows:

- Shaft - The generator shaft material is "Inconel 750", a non-magnetic heat treatable material that has process capability to provide a yield strength of 125,000 psi. The shaft is hollow so as to minimize weight. Heat treatable shaft extensions of 4140 material where inertia welded for the bearing journals and spline interfaces.

- Hub - The hub material is "Inconel 750" and is heat treated to provide 125,000 psi yield strength properties. The hub provides the base or support for attachment of the spoke configured magnetic members and the permanent magnets.

- Permanent Magnets - The permanent magnets produced from fine particle rare earth-samarium cobalt magnet alloy, sintered, magnetic particle aligned, and heat treated to provide an Energy Product of not less than 20×10^6 (B_d, remanent induction x H_d, demagnetization force) measured at room temperature. The magnets are assembled in the rotor structure in the fully magnetized condition.

- Magnetic Member (Spoke Configured) - The spoke configured magnetic member was fabricated from 1010 steel and attached to the hub of Inconel 750 by electron-beam weldments.

- Shrink Rink - The shrink ring is a bi-metallic member consisting of Latrobe's MP35N, a non-magnetic heat treatable material which is positioned over the permanent magnet in the rotor configuration, and 300 maraging steel, a heat treatable magnetic material which is located over the magnetic members. These members are assembled alternately and welded by the electron beam process to form the ring.

- Rotor Assembly - The spoke configured magnetic hub assembly is expanded diametrically to provide a slight increase in slot opening. The permanent magnets and wedges are positioned between the spoke segments (wedges are applied as necessary to achieve a tight fit circumferentially), and the hub is released causing side forces to secure the magnets in position.

  The outer diameter of the hub magnet assembly is machined to required dimensions and then the shrink rings, which contain the electron beam welded magnetic and non-magnetic members, are aligned to provide the proper magnet path and assembled over the finished assembly using a shrink-fit of sufficient pre-stress to assure centrifugal loads on the ring at maximum speeds are below the stress produced by the shrink.

  The aforementioned hub/magnetic/ring assemblies are aligned and assembled to the shaft with a slight shrink fit to complete the rotor body assembly. The rotor body and shaft are keyed to retain alignment.

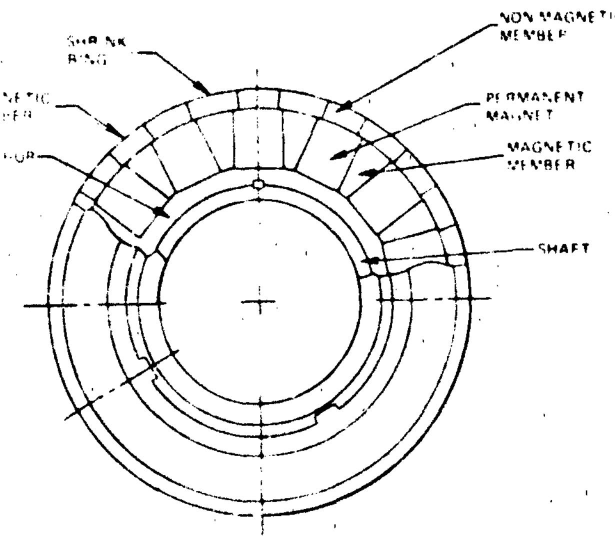


Figure 33. Rotor Cross-Sectional View

4.2.1.1.2 Stator Wound

The stator is constructed with a wound laminated magnetic core, an outer aluminum shroud and a frame of high strength aluminum alloy. See Figure 34. The laminated core is 7.0 inches in length, has 63 slots and contains a nine-phase, multiple strand, round conductor winding. The stator slot is overhung to minimize the pole face losses.

- Stator Core - The stator core is constructed with laminations fabricated from 0.006 inch thick vanadium-colbalt-iron, an alloy commonly known as "Vanadium Permendur". See Figure 35 for picture of the lamination. This alloy, when properly processed, permits design for operation at substantially higher flux densities with lower magnetizing current than conventional magnetic steels, thereby permitting a lightweight electromagnetic design. The 0.006 inch thickness was selected to minimize eddy current losses at the high operating frequencies.

  The laminations were stacked and aligned, and secured by bonding.

- Phase Winding - The phase coils are wound with quadruple build polyimide enameled round copper conductors. The quadruple build polyimide insulation is applied to enhance phase-to-phase and phase-to-core insulation reliability.

  The coil turns are wound in strands, or in multiple, to reduce "skin effect" I^2R losses. The strands are transposed in the end turns such that top positioned conductors entering the slot are transposed to a bottom position with respect to the slot in the end turn region at the opposite end of the slot. This transposition has the effect of cancelling strand-to-strand voltages generated in the slot and thereby reducing "deep bar" I^2R losses.

- Connections and Leads - The terminations of phase windings are brazed with connections of each phase made to a multiple wrap polyimide film insulated stranded copper cable.

- Winding Impregnation - The completed stator winding is impregnated with General Electric Novalac compound, applied by multiple vacuum-pressure processing. This compound and process assures maximum slot fill and coil bond to affect best transfer of heat from the slot into the core, aluminum shroud and cooling oil in the frame.

- Stator Insulation - The stator slot ground insulation consists of a .005 and .003 inch polyimids strips. The two slot liners were used to obtain good mechanical and electrical ground insulation. A .003 inch phase separator was placed between the top and bottom conductors and extend out of the slot.

An end turn seal sleeving was applied to the end turns to minimize the oil leakage between the stator end turns and the core. This was to minimize oil that would get into the air gap and cause additional losses. It was also installed in such a way as to increase the end turns cooling.

Figure 34 shows a completed stator wound.

To get a good ground insulation at the slot opening, a .005 polyimide inverted slot liner was placed over the top phase. This was done rather than trying to fold the ground slot liner under the top stick. A top stick was installed inside the ground slot insulation and under the stator tooth overhang. In the end turns a .003 thick polyimide insulation was placed between different phases and was overlapped with the slot phase insulation at the end of the slot. The slot phase insulation was allowed to extend out past the ground insulation.

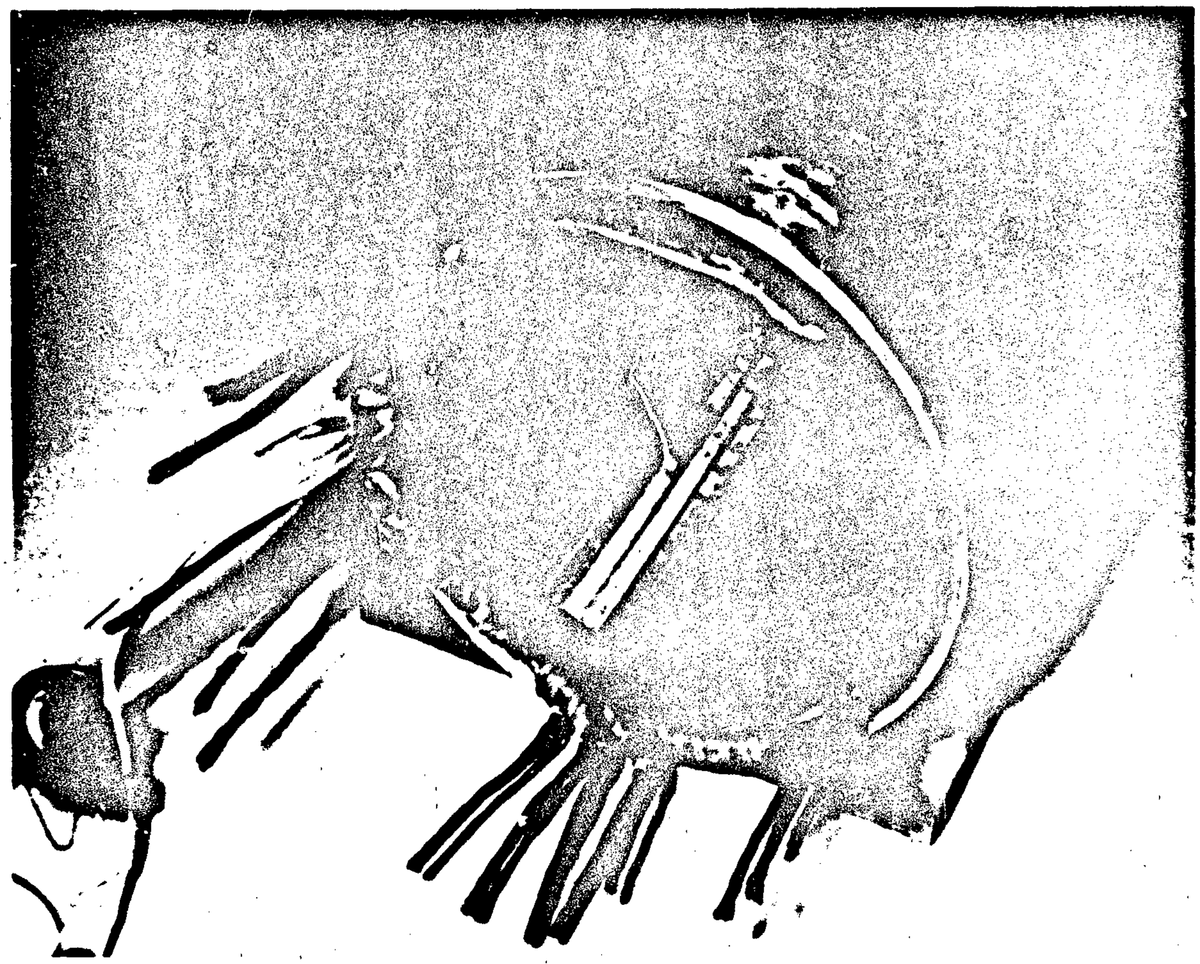


Figure 34. Stator Wound

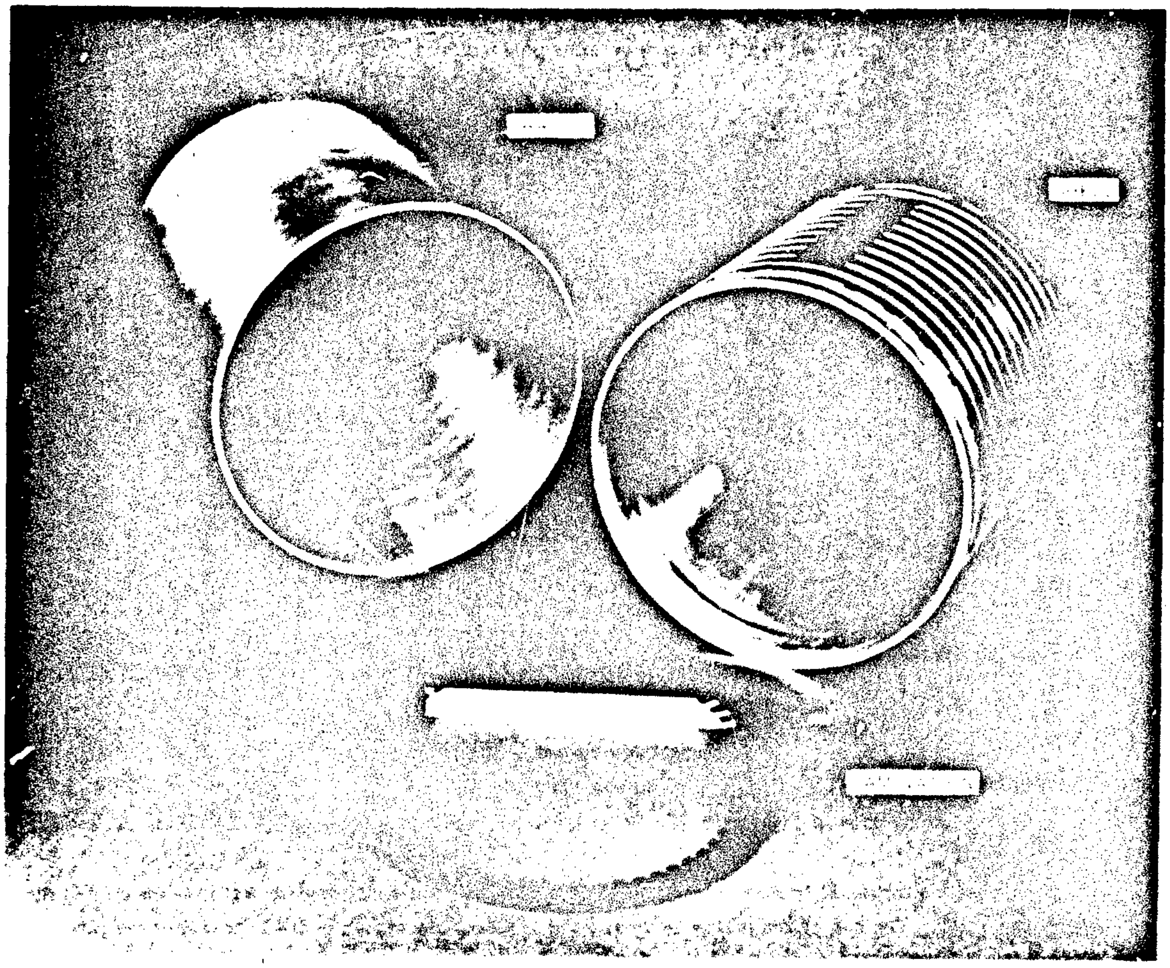


Figure 35. Stator Lamination with Oil Shell and Shroud

4.2.1.1.3 Bearings

The main generator bearings used are deep groove, single row, single width, open type of radial Conrad construction. The bearing balls and rings were vacuum melted AISI M50 tool steel, heat stabilized, and manufactured to ABEC-7 precision tolerances.

The drive end bearing outer race is clamped (fixed) against shaft and bearing housing shoulders and the anti-drive end bearing is assembled to allow axial movement in its housing. The outer race of the anti-drive end bearing is preloaded by a spring washer to assure reliable performance of both bearings throughout the generator speed range.

The lubrication and cooling of the bearings is provided by an oil jet.

4.2.1.1.4 Seals

Arecision carbon face seal is located at the outboard end of the drive end bearing. The function of this seal is to contain the bearing oil in the generator cavity.

The seal is a steel seal ring pressed onto the shaft and forms the rotating member and a stationary spring-loaded carbon ring which is retained by the bearing housing. The seal ring of AMS 5322 steel rotates against the stationary carbon member to form the dynamic seal. The face of the seal ring is plated with hard chromium (AMS 2406) to assure long life and is precision lapped.

4.2.1.1.5 Disconnect

This electromagnetic disconnect described below was developed and tested on another program and was applied on this program.

A cross sectional view of the disconnect assembly in the engaged position is shown in Figure 36. Nomenclature assigned to the disconnect component parts are used herein to describe operation of the disconnect and are identified by name and number in Figure 36. See Figure 37 for disconnect assembly on the generator.

In the engaged position torque is transmitted through the drive shaft and a torque tube that is connected to the outboard clutch plate. The two clutch plates (outboard and inboard) use curvic gears to transmit the power. The inboard clutch plate is splined to the rotor shaft.

4.2.1.1.5.1 <u>Disconnect Operation</u> - To disconnect the drive system from the rotor the two clutch plates are required to separate in the axial direction so that the curvic gears on the plates disenage. The following events are required to achieve a disconnect.

1. Power is applied to the magnet coil assembly. The magnet iron and coil are of ring configuration that encircle the shaft such that the flux travels around the coil and in an axial and radial direction as shown in Figure 4.2-6.
2. The magnetic force pulls the armature inboard towards the magnetic coil. Normally, the armature is held outboard by a spring.

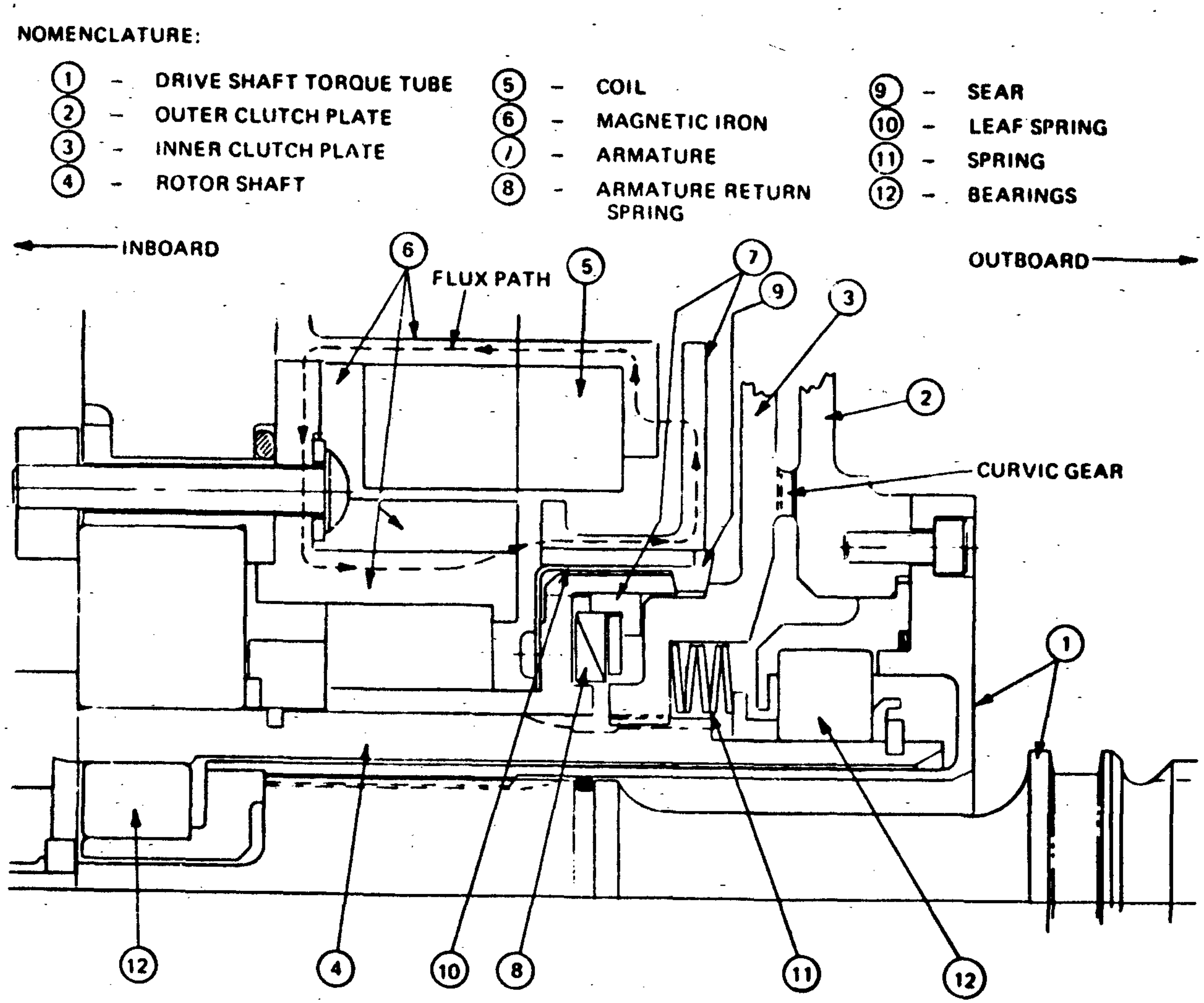


Figure 36. Disconnect Operation

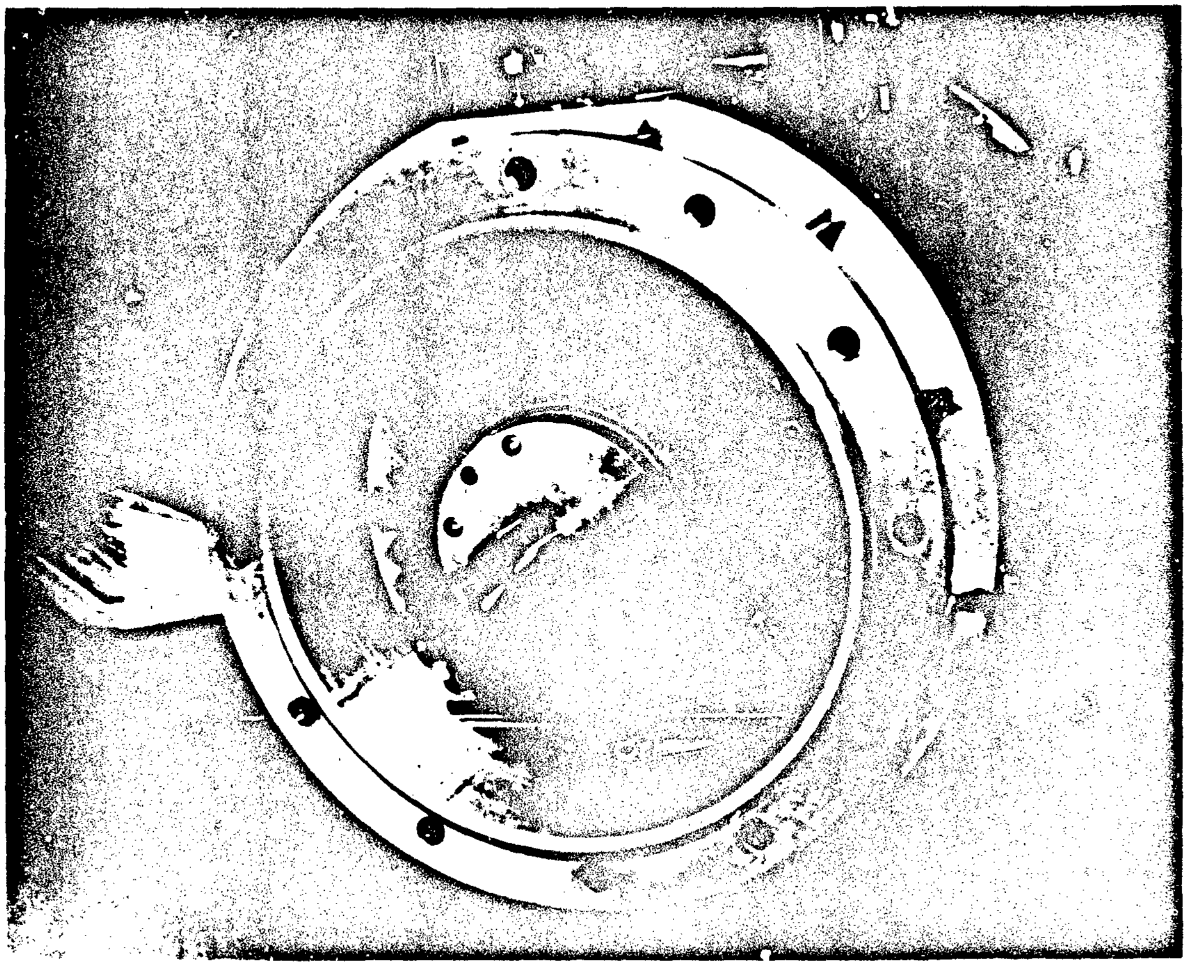


Figure 37. Disconnect Assembled

3. The motion of the armature inboard pulls the armature away from the outer surface of the sear. The sear is comprised of three segments in the radial plane which are equally spaced in the circumferential direction. A thin leaf spring portion of the sear is attached to the sear support at the inboard end of the spring. The leaf spring is pre-stressed so as to force the sear inward radially.

4. The sears move outward in a radial direction. The axial force of the springs located between the clutch plates together with shape of the curvic gear teeth produce an axial force on the sear. This axial force causes the sear to flex outward. The contact angles between the sear and the clutch plate and the sear and sear support is such that the axial force produces a radial force on the sear. This radial force also exists when the sear is released and slides on the clutch and sear support. The contact angles are such that the parts are not self-locking because of the coefficient of friction on the sliding surfaces in the disconnecting mode.

5. The clutch plates separate in the axial direction and disconnect in the rotor from the drive shaft.

The axial force described above also causes the clutch plate to slide on a splined shaft. Springs also hold the two clutch plates apart after disconnect. The bearings allow the drive shaft and the outboard clutch plate to rotate while the inboard clutch plate, rotor shaft and other disconnect parts remain stationary.

4.2.1.1.5.2 Re-engagement of Disconnect - To re-engage the disconnect, the inboard clutch plate is moved outboard against the springs located between the two clutch plates. The mechanism for moving the inboard clutch plate is detailed as follows.

When the inboard clutch plate is moved to the outboard position, the sear flexes inward between the sear support and the inboard clutch plate. The leaf spring portion of the sear produces the inward force. After the sear flexes inward, the armature spring forces the armature over the sear and locks the sear in place so that the two clutch plates cannot separate.

4.2.1.1.5.3 Reset Operation - The reset operation of the disconnect is described with aid of Figures 38 and 39 as follows.

To reset the clutch plate, the rack is pulled outward. This action causes the support to rotate. The slide and idler members move by spring action causing the gear idler member to engage the teeth on the two clutch plates and align them with each other. This alignment event occurs during a portion of the travel of the rack and support. When the teeth on the outer diameter of the clutch plates are in line, the clutch plates curvic gears can be engaged. As the rack is pulled further, the cam bearing moves axially on a cam surface and forces the clutch bearing to move the clutch plate outboard. (See Figure 40.) With this motion the disconnect mechanism reconnects as previously described. There are six bearings on the support used to apply a uniform force between the cam surface and the clutch plate. The rack is pushed inward, which disengages the bearing and the idler, and is held in position by a "Faspin." (See Figure 38.)

4.2.1.1.6 Power Termination

The power leads are terminated on two terminal blocks which have six studs per block. This provides connections for the 9 phases and 3 neutral leads. Each neutral lead contains the return for three phases that are 120 electrical degrees apart. This was done to cancel out the high frequency loss associated with passage of an AC signal thru a metallic wall. See Figure 41.

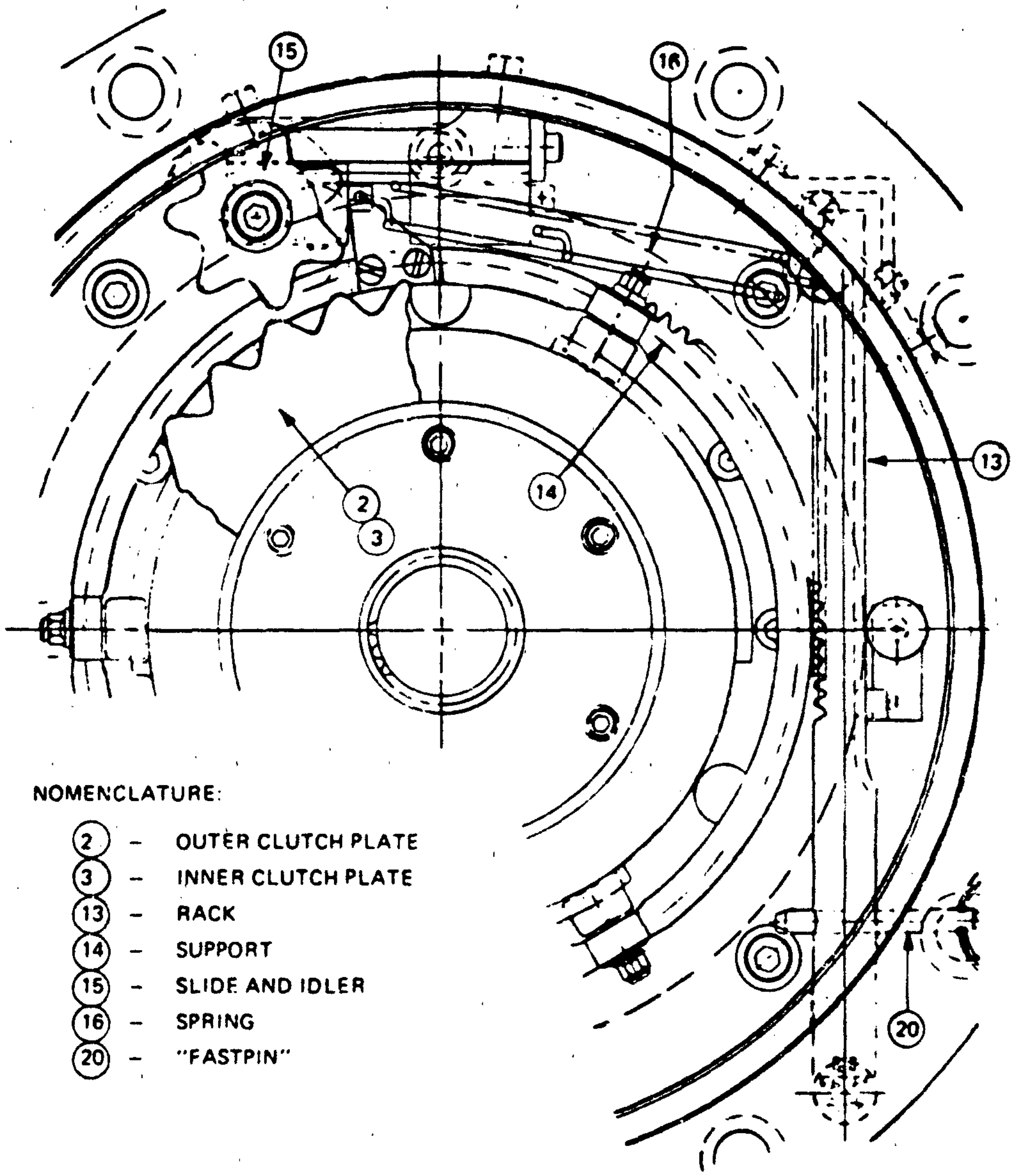
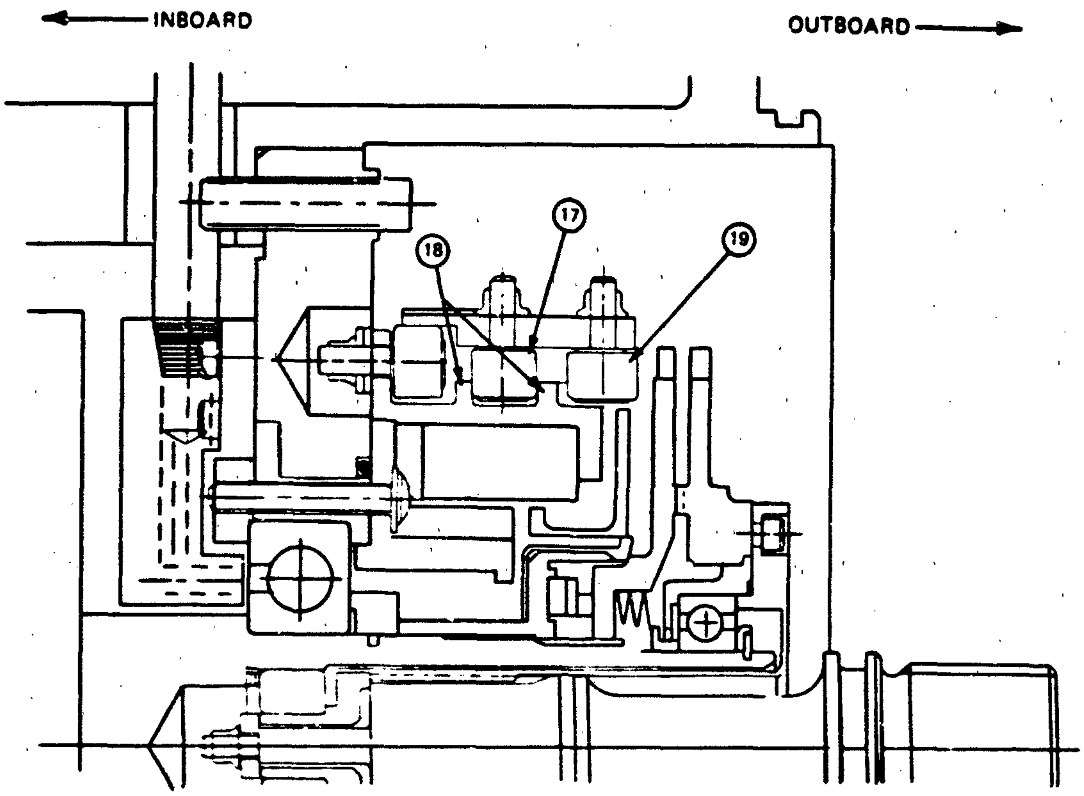


Figure 38. Reset Axial View



NOMENCLATURE: 17 – CAM BEARING
18 – CAM
19 – CLUTCH BEARING

Figure 39. Reset Operation

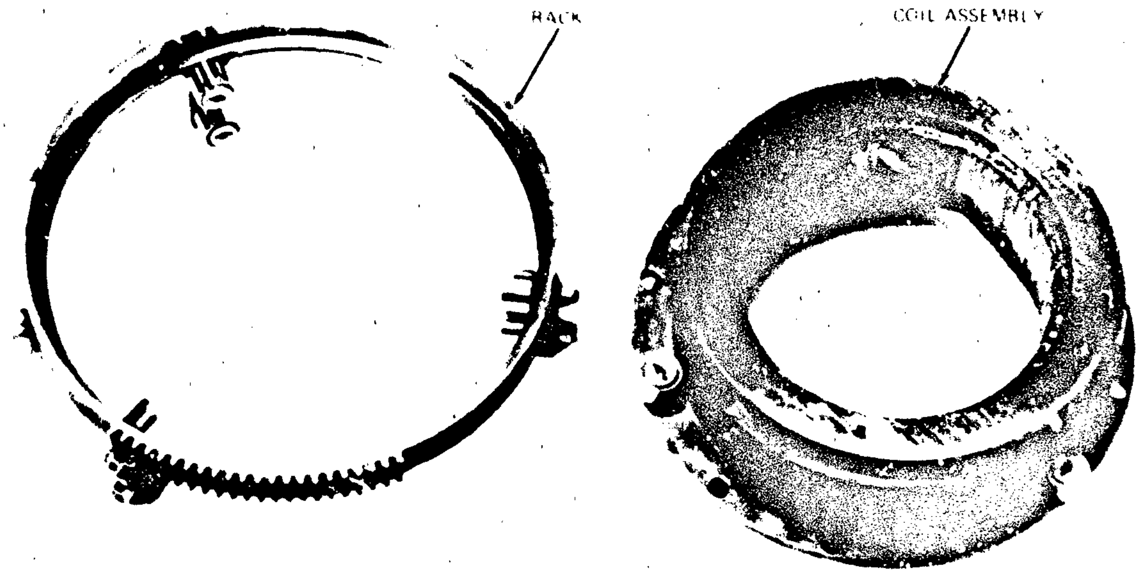


Figure 40. Disconnect Reset Rack and Disconnect

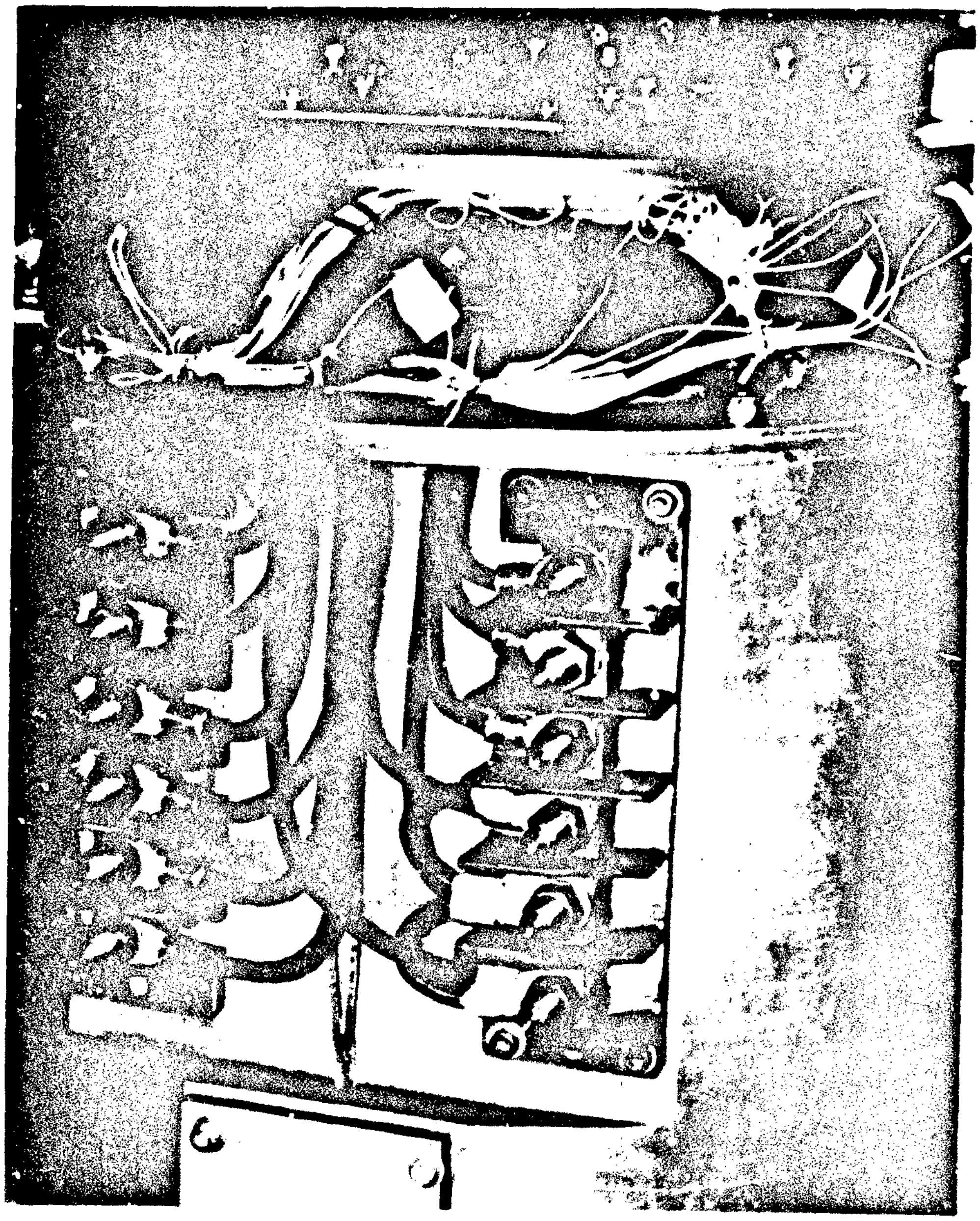


Figure 41. Generator Terminal Block and Lead Assembly

4.2.1.1.7 Stator Cooling

The shell, See Figure 35. has circumferential groove cut into it which serves a rectangular oil passages when the shroud is installed over the shell. There is a radial hole through the shroud that when assembled with the shell lines up with axial manifold in shell. Oil flows through the hole in the shroud, through the axial manifold to the circumferential oil passages to a second axial manifold at the bottom of the shell not shown in the figure. This manifold is longer, axially, than the top manifold and connects to circumferential grooves at each end of the shell. Oil is then passed through the holes in the shell onto the end turns causing an oil spray cooling of the end turns.

4.2.1.1.8 Pump

The oil circulating pump is a positive displacement pump sized to supply the required oil flow at minimum generator speed. At high speed, the pump output will be somewhat higher than required. The pump is driven by a reduction gear that meshes with a spur gear on the anti-drive end of the rotor shaft. See Figure [illegible]. Figure 43 shows the oil pump assembled as removed from the generator

4.2.1.1.9 Pressure Relief Wave

A pressure relief valve is used in the oil system to limit the pressure to the generator and external oil system. See Figure 43 for location. When there is an excess pressure, caused by an increase in the pump flow, the valve will open and maintain the pump and oil system pressure.

The valve is made of aluminum with a "Teflon" O-ring and is adjusted to the desired pressure setting prior to being installed in the pump housing support.

4.2.1.1.10 Sight Glass

A sight glass located on the anti-drive end of the generator as shown in Figure 44 is used to determine the oil level. The oil level must be determined during operation due to the external oil loop.

4.2.1.1.11 Temperature Sensor

Four copper constantan thermocouples are located in stator slot opening approximately 90° apart and in middle of the stator stack length. See Figure 45.

4.2.1.1.12 Current Unbalance

A multi-turn, single coil current transformer is positioned around each phase neutral lead and is located within the generator. See Figure 46. The input lead of each transformer is connected to the control connector and the output leads are connected at a common bus inside the generator with one lead returned to the control connector.

These current transformers provide a signal to the converter with indication of phase current unbalance and therefore help monitor phase unbalance due to loads or faults.

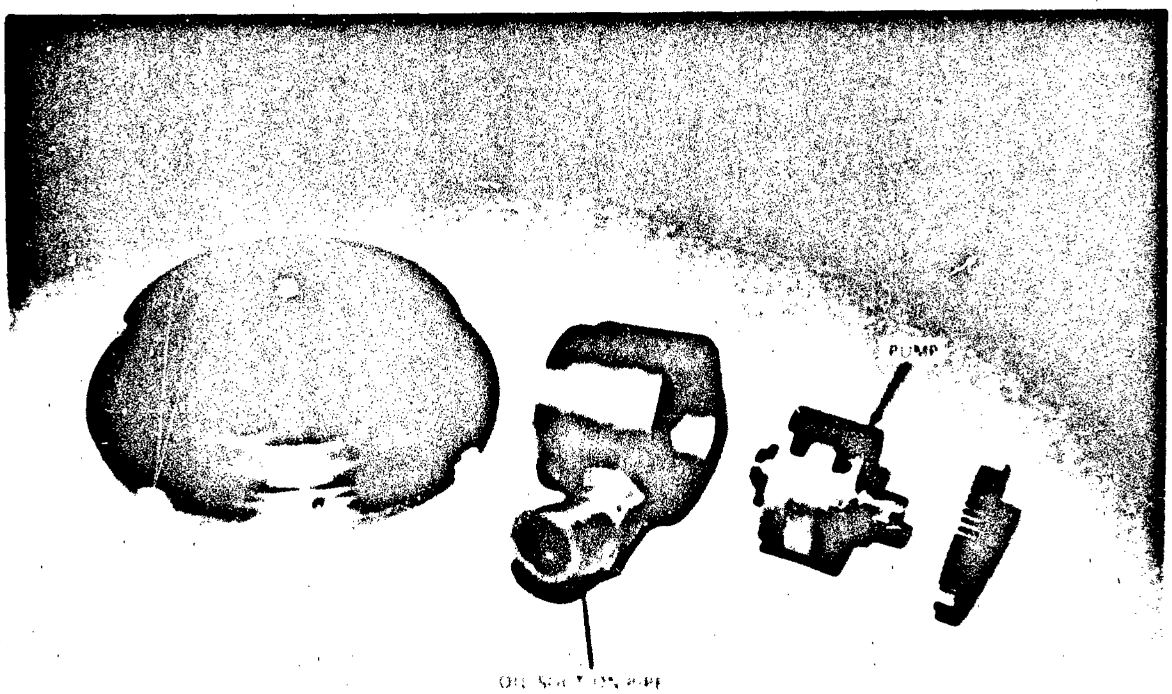


Figure 42. Generator Oil Pump and Assembly Component

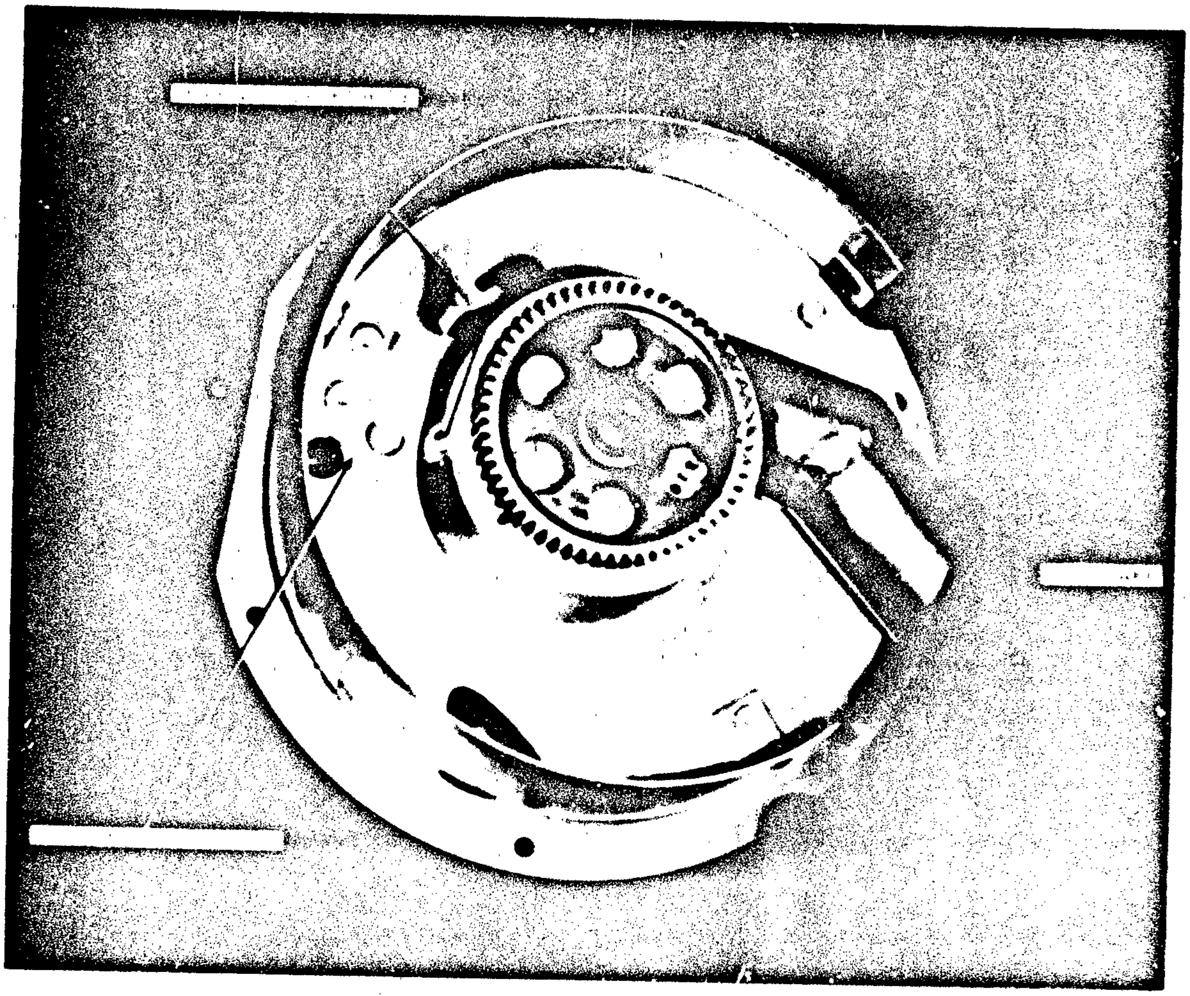


Figure 43. Generator Oil Pump Assembly

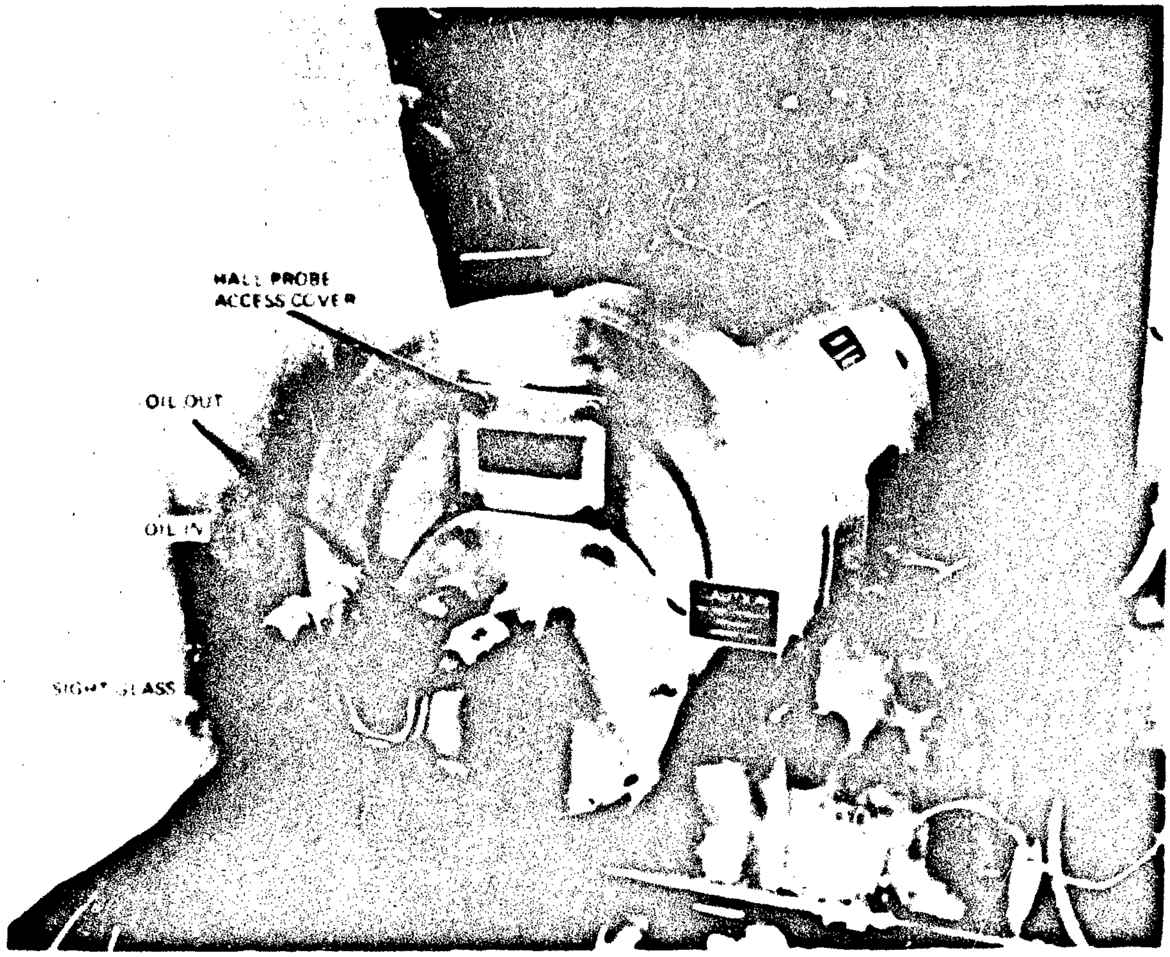


Figure 44. Generator Oil Connection and Sight Glass

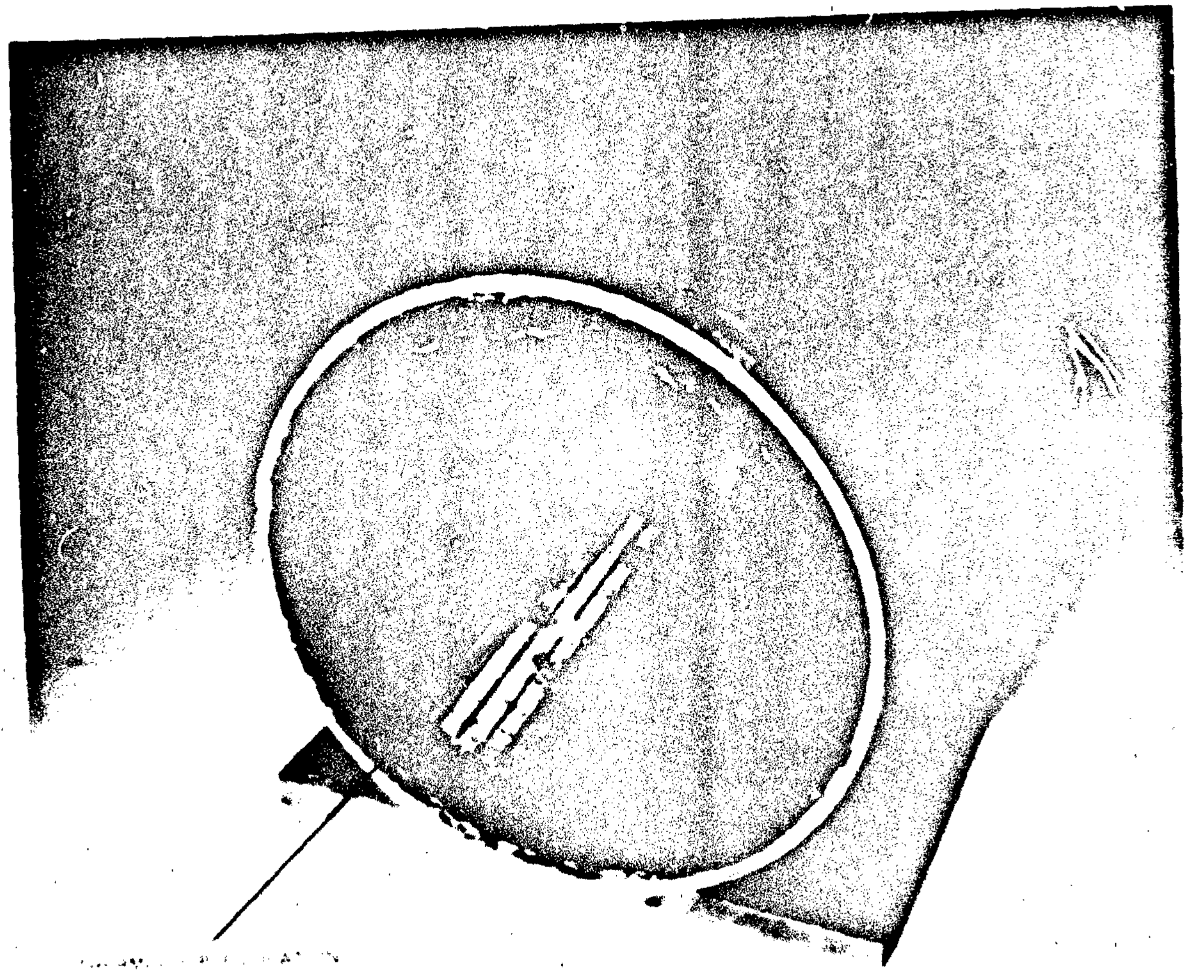


Figure 45   Generator Thermal Sensor Location

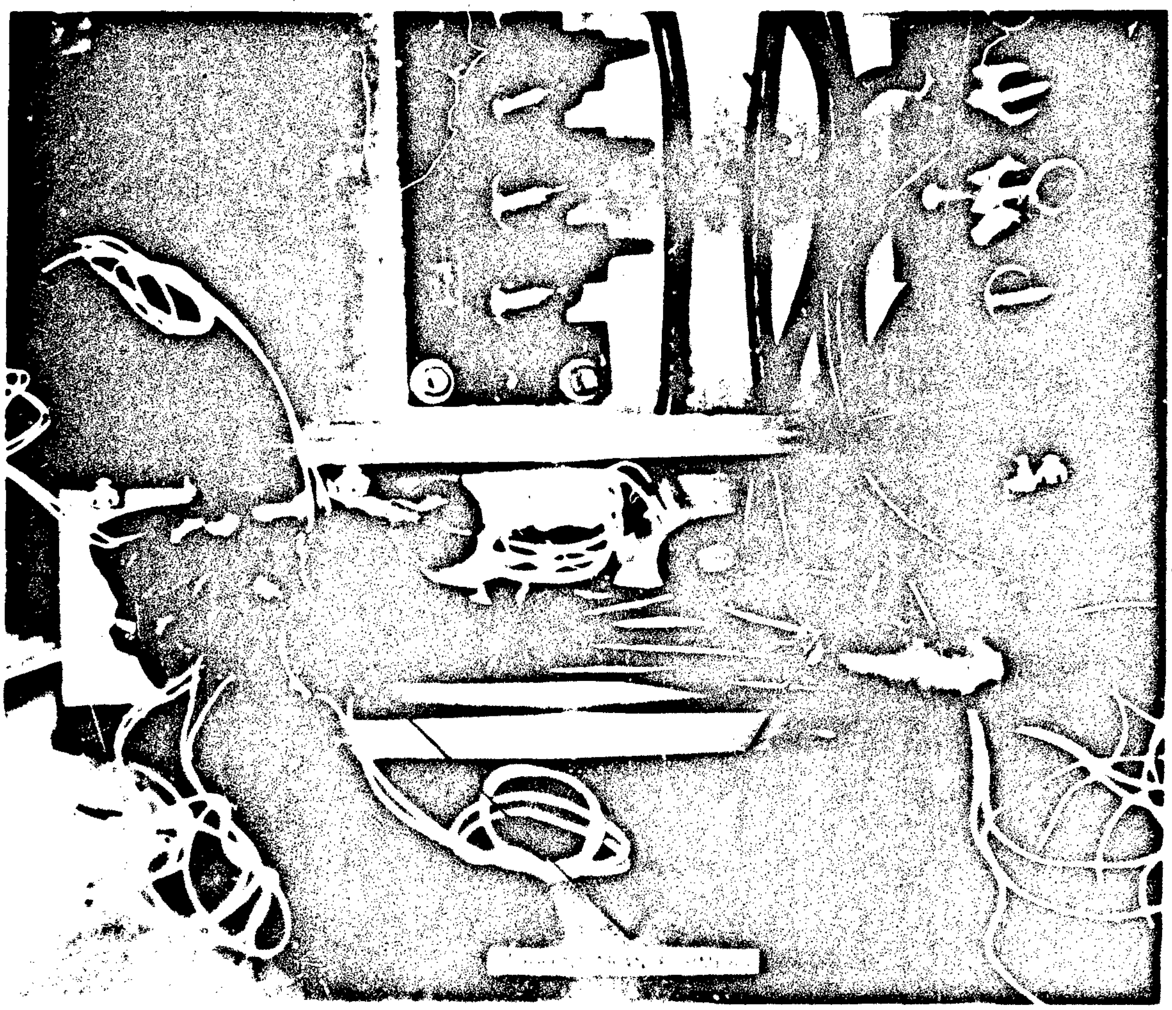


Figure 46. Generator Current Transformer Location

4.2.1.1.13 Speed Sensor

Three Hall effect elements will be used to provide rotor position and rotor speed sensing. See Figure 47. The Hall effect element provides an output signal as a function of magnetic flux. The Hall effect elements are located on the anti-drive-end shield, are separated 120 electrical degrees, and are positioned so as to detect the pole leakage flux of the permanent magnet generator. Adjustment screws in the Hall support permits precise sensor adjustment axially and circumferentially. See Figure 44 for location on generator.

A small sensor core of laminated silicon iron laminations is utilized to increase the magnetic flux through the Hall element. The leads of the Hall effect device are covered by a shield to eliminate noise signals that might be generated in this signal device. The shielding is terminated adjacent to the control connector and the Hall generator leads are terminated in the control connector.

4.2.1.1.14 Frame and Support Hardware

After a failure that damaged the original cast magnesium frame, it was necessary that the frame be replaced. This replacement frame and the other structure parts were machined from 1010 aluminum. Consideration in the design of these parts where in machining time to provide a fast replacement. Weight was not a prime consideration.

Figure 48 shows these parts.

4.2.1.2 Generator Design

The details that were used to establish the rotor design and fabrication techniques as well as the stator design are covered in the 150 KVA SAMARIUM COBALT VSCF STARTER/GENERATOR ELECTRICAL SYSTEM Phase I Technical Report, AFAPL-TR-76-8. The following paragraphs address themselves to areas where further investigation or design analysis were made to study problems that were encountered in the assembly and testing of the generator.

- Throughout the 100 hour rotor endurance test and the initial no-load generator testing, high vibration and loss of rotor balance were continually observed. The rotor natural frequency was calculated and tests were performed to determine optimum bearing preload.

- Losses at no-load measured by oil heat rejection were higher than calculated and the rotor surface showed signs of higher than anticipate temperatures due to noticeable discoloration. The losses were calculated and, where possible, were verified by test from which a thermal analysis was made on the stator.

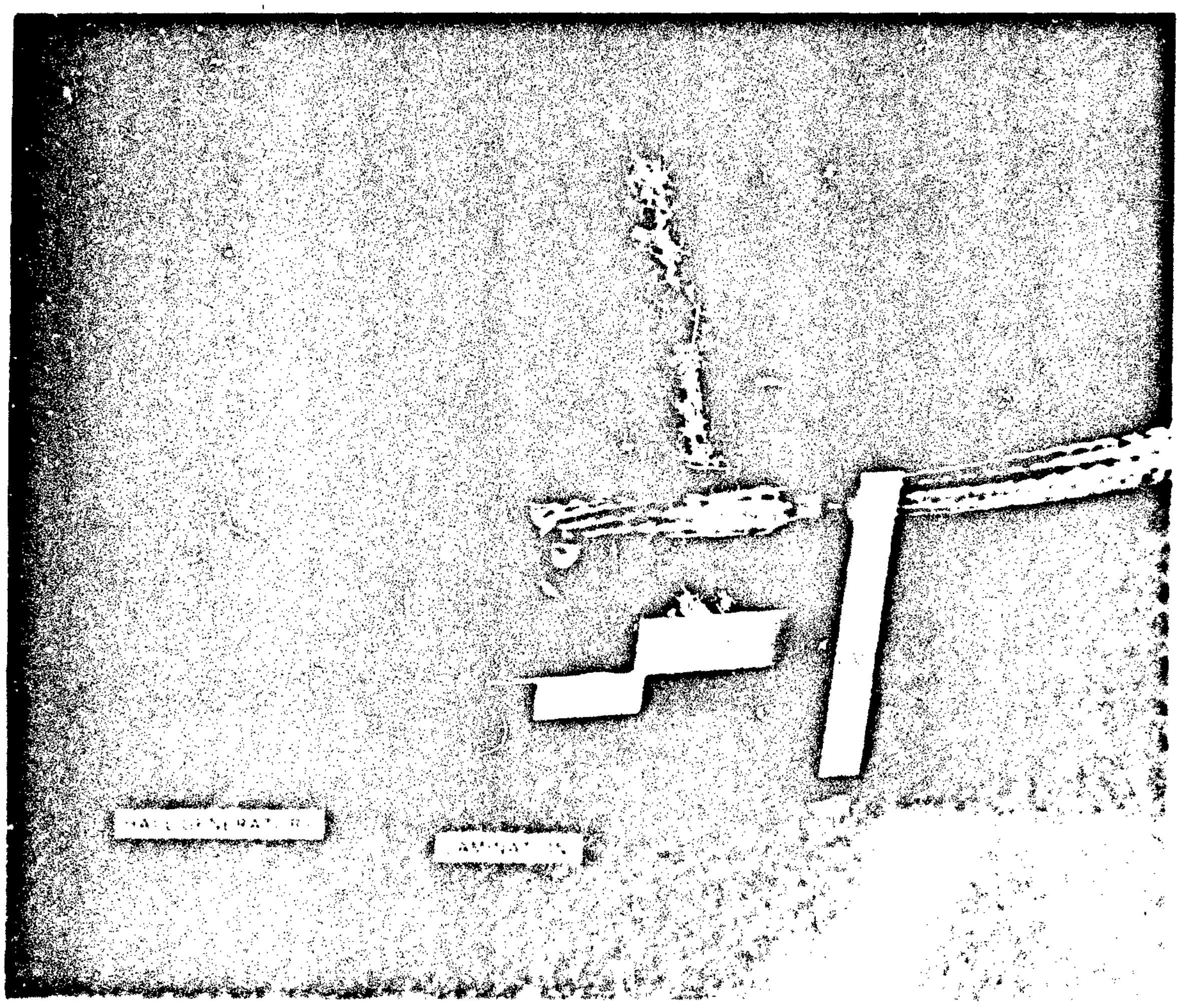


Figure 47. Generator Hall Probe Assembly

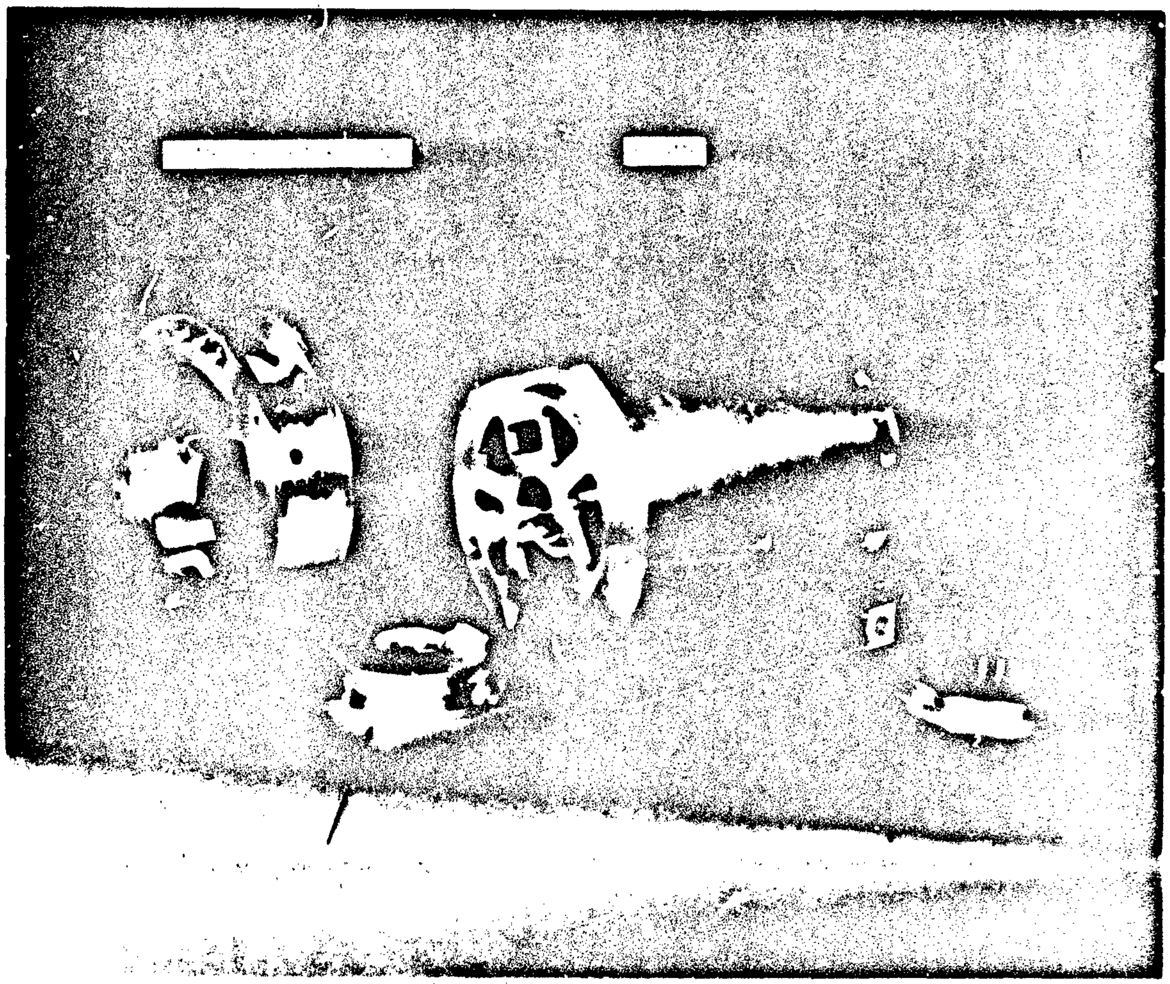


Figure 48. Generator Frame and Support Hardware

4.2.1.2.1 Shaft Critical

4.2.1.2.1.1 Shaft Critical Speed Calculation - A computer program for shaft critical speed applicable to a two bearing machine with or without overhung loads at either end, which for analysis permits the shaft to be separated into a convenient number of sections was used. This computer program takes into account the magnitude and location of the applied load, the type of support bearing used and the transverse flexibility at the bearing supports. This program also takes into account variations in the inside and outside shaft diameter, as well as tapered sections.

The above described program was used to calculate the shaft critical speed of the rotor. The first critical speed was calculated to be 25,380 rpm which agrees with the value calculated during the Phase I 100 hour rotor endurance testing.

This computer program calculates the critical speeds but does not provide information as to the threshold of where the frequency response curve starts to break away. A common design approximation, to assure a safe operating margin from this threshold point, is to design the shaft critical to be at least 25% higher than the top operating speed.

It is evident that this margin was not provided in this shaft design and part of the vibration problem being experienced can be attributed to the shaft critical being too close to the top operating speed range.

4.2.1.2.1.2 Rotor Natural Frequency Tests - The shaft critical speed is affected significantly by the bearing stiffness which can be varied to some degree by the bearing preload. It was concluded that tests must be run on the rotor assembly to determine how much the rotor natural frequency could be increased by increasing the bearing preload.

The tests that were conducted measure the natural frequency of the rotor by recording the response of the rotor when excited by hitting it. This test was performed using the spin test fixture from the 100 hour rotor endurance test. Two, one and three-quarter inch holes where drilled into the frame to provide access to the rotor as it would be mounted in a wound stator. Directly in line with these holes, two aluminum blocks were bonded to the rotor surface. One block served as a means to mount an Endevco 22210 Piezo-electric accelerometer while the other one served as a striking plate. The output of the accelerometer was fed thru a 1 kHz low pass filter to an oscillate scope. The scope was set to trigger when the rotor was excited (strike the plate on the rotor surface with an aluminum drift held firmly in place and tap lightly with a 4 ounce hammer). The scope display was recorded on a photograph from which the time duration of one pulse could be determined and the natural frequency could be calculated.

The above test was conducted for the following bearing preload conditions:

Number Wavy Washers	Approximate Bearing Preload (lbs)	Natural Frequency (RPM)
0	0	21,397
1	64	23,077
2	128	31,734
3	192	32,142

Different modes of excitation, such as frame hits in various areas, and higher cut of frequencies on the filter, 10 kHz and 15 kHz, where tried without changing the resultant natural frequency significantly.

A similar test as described above was done with the rotor bearing journals being supported on sharp edges instead of on bearings in a frame. The result of this test showed the rotor structure, by itself, to have a natural frequency of 120,000 rpm. This value is very close to the value obtained by a balance vendor who had reviewed this type of rotor structure for possible application of high speed balance techniques.

The above tests indicate the major limiting area to increasing the shaft critical speed to be in the bearing. Increasing bearing pre-load is advantage up to two wavy washers. The use of a third wavy washer does not indicate sufficient increase in shaft critical to justify lowering the bearing life. Therefore the optimum bearing preload was set at two wavy washers.

4.2.1.2.2 Rotor Balance

4.2.1.2.2.1 High Speed Balance - A noted balance vendor, who had developed a high speed balance machine, was called upon to review the rotor design and construction and comment on the feasibility and requirements to accomplish a high speed balance on the rotor. Based on his measurement of the rotor structure natural frequency being above 100,000 rpm, it was responded that a high speed, three plane balances was not necessary because it was a rigid structure. It was suggested that a two plane high speed at elevated temperature would be beneficial but would be of no use unless the balance was repeatable. The experience with balance on this rotor was that when it was balanced it would follow a similar vibration vs speed curve up to a speed between 16,000 to 18,000 where a shift would occur and the vibration would be significantly higher. Indications where that increased temperature ambients lowered the speed level at which the balanced shift occurred.

Various attempts were made to improve the balance by lowering the acceptable balance limits and performing the balance with the rotor at various temperatures up to 100°C without conclusive improvement in balance.

It was theorized that parts inside the rotor were sliding, the magnets were disintegrating, or the balance was being shifted due to operating the assembled rotor near shaft critical causing this balance shift.

4.2.1.2.2.2 Rotor Disc Preload - After the second generator failure occurred, the balance problem went from a level where it could be tolerated, 3 g's rms on outboard two of generator at 18,000 rpm, to being totally unacceptable, 7g's rms on the outboard end of the generator at 16,000 rpm after a brief warmed up period.

While making a visual examination of the rotor, it was noticed that there were gaps between three discs where it had noticed before and document in the phase I report that there was one (page 133, paragraph 6.4.2). These three gaps were measured to be approximately .003 inches with feeler gauges. It is to be noted that the rotor diameter was measured in seven places and the stack length was measured in seven places as part of the 100 hour endurance test and in the same locations after both failures and a only a slight change in overall length was noted which did not appear to be significant.

It was decided that the shaft nut, that serves as a shoulder to hold the discs onto the shaft, should be checked for tightness. Due to not having a suitable means to hold the rotor and apply a known torque to the nut, an impact wrench was used on the nut with the rotor sitting in a V-block with a rubber mat wrapped around it. The nut could be engaged further and it was noticed that the gaps between the discs started to close. Upon closing one gap completely and most of a second gap and noting that the shaft nut had begun to dish slightly (threaded I.D. of nut face in farther than O.D.), it was decided that the rotor should be assembled in the spin test fixture so the centrifugal force of rotating the disks at speed without rotor heating due to pole face losses, should aid in releaving and further relation of the discs axially to their seated position. During this rotor spin, vibration levels were obtained that were approximately one half the values shown in Figure B-1 page 144 of the Phase I report. After running at 22,000 rpm, a shift in vibration was noticed. The vibration increased to 4.5 g's rms at 21,000 rpm where the Phase 1 test had been 7 to 9 g's. The rotor was removed from the spin test fixture and only one gap existed part-way around (60^{o}) the diameter where it had been almost all the way around the rotor diameter before the spin.

The shaft nut was tightened further and was mechanically staked after the rotor was spun in the stator/frame, confirming that the vibration shift was solved. This tightening of the nut has resulted in a decrease of approximately .0065 inches in the rotor stack length from the November 21, 1977 measurement.

It is concluded that the cause of the shift in balance continually experienced was due to the nut tightening and staking method used when the rotor was originally assembled. This is partially correct but it is felt that the main cause was that when the disc was assembled, the shaft and discs were not in a stabilized or normalized condition. The shaft was cooled in liquid nitrogen to shrink it and enable assembly of the discs.

What is recommended is that the rotor assembly be thermal cycled between the maximum and minimum temperature extreme at least two times and subjected to rapid acceleration in speed prior to the shaft nut being staked permanently. All of the above being accomplished with a shaft nut providing an axial pre-load on the shaft.

4.2.1.2.3 Generator Losses

The generator when it was assembled and checked for proper operation at no-load for the first time, was found to have high heat rejection. This was measured by the oil temperature rise across the generator, which was considerably higher than had been calculated. Shown below is the comparison of no-load watts, calculated and measured.

Speed RPM	Calculated Losses	Measured Losses
12000	3800	5000
16000	6500	8500
21000	9700	--

A study of the loss breakdown was initiated to determine whether the results obtained were correct or in what area were the losses not calculated properly. A major concern was the loss attributed to a solid pole face. The areas of study were broken down as follows:

- Electrical Losses
  - Pole Face
  - Core Loss
- Mechanical Losses
  - Friction
  - Windage

4.2.1.2.3.1 Mechanical Losses - The mechanical friction type losses associated with the seal bearings, and oil pump are relatively low with respect to the other losses and are typically neglected.

For purposes on loss breakdown, the oil temperature rise measurements at no-load were made with the generator oil pump and without the generator oil pump to verify that the oil pump loss was insignificant. The results of this test showed there was no noticeable difference in the oil temperature rise through the machine. Thus the oil pump was not contributing to high losses.

4.2.1.2.3.2 Windage Losses - The windage loss associated with the permanent magnet rotor was calculated based on a smooth cylinder with straight ends. The air gap along with end gaps on the rotor were used to perform this calculation. The data listed below is the result of this calculation for a specific density and viscosity condition of air.

Speed In RPM	Windage Loss in Watts
12000	105
16000	253
21000	500

The above windage results, when compared to a wound generator, are many order of magnitudes less. The windage loss associated with a solid rotor is expected to be less, due to the lack of salient features. But how much less was not known due to the lack of experience with a similar size and shaped object rotating at these tip velocities.

It was concluded that the windage loss must be measured on the generator. This presented a problem in that the rotor magnetics could not be turned off to remove the pole face loss and the stator core loss.

A spin fixture, that was used to develop the disconnect on another program, had a dummy rotor of similar size, (6 '' diameter and stack) as the samarium cobalt rotor. The frame of this spin fixture was modified by adding a solid steel yoke with a 250 finish on the inside diameter so the stator lamination surface affect and the airgap of the actual machine could be simulated. The stack length of the rotor was increased to 7.0''. This spin fixture had oil mist lubricated bearing which enabled this fixture to closely resemble the actual generator.

This fixture, as modified to simulate the actual machine, was driven at the various generator operating speeds and the torque (friction and windage losses) was measured by torque head mounted between the spin fixture and the drive stand. The results of this test are shown below.

Speed In RPM	Windage Loss in Watts
12,000	1400
16,000	1800
21,000	2300

This data verified that the windage loss was considerably higher than had been calculated. The error in the calculation is felt to be due to not taking into consideration the stator slot opening and stator bore surface roughness as well as the viscosity change to the atmosphere inside the machine being an oil mist rather than air alone.

4.2.1.2.3.2 Electrical Losses - The electrical losses for this permanent magnet type generator are separated into three major categories. These classifications are (1) laminated stator core losses caused by hystersis and eddy currents, (2) pole face losses resulting from the heating effects of the high frequency flux wave at the airgap surfaces of the shrink ring magnetic members, and (3) the I^2R losses generated by the resistance of the copper to current flow.

4.2.1.2.3.2.1 Core Losses - The core loss is calculated from the core weight which is comprised of the stator yoke and teeth. The core loss in watts per pound is based on (1) the operating level of induction in the tooth and core sections, (2) the frequency of the generated voltage wave, (3) the material thickness, and (4) the type of annealing process.

The calculated core loss for this generator is listed below as follows.

Core Section	Core Weight-lbs.	Core Loss - Watts Per Pound					
		12,000 rpm 1400 Hz		16,000 rpm 1860 Hz		21,000 rpm 2450 Hz	
		No-Load	Full-Load	No-Load	Full-Load	No-Load	Full-Load
Yoke	12.5	1629	1378	2506	2005	4010	3258
Tooth	5.9	986	767	1480	1315	2192	1863

It is to be noted that the Phase I Report page 34 data was calculated on the basis of .010 inch thick laminations where .006 inch thick laminations were used in the stator that was built. The .006 inch laminations were used in order to keep the core losses as low as possible and still maintain a high flux density in the stator core.

4.2.1.2.3.2.2 Pole Face Losses - Pole face losses are composed of eddy current and hystersis type losses. The magnetic flux density at the pole face opposite a tooth is greater than that opposite a slot and as the rotor rotates the pole face is subjected to a pulsating flux density causing eddy currents to circulate in the pole face causing losses on the pole face surface. The hysteresis losses are overshadowed by the eddy current losses due to the high tooth frequency and are therefore neglected. The following discussion on pole face losses therefore relate to eddy current type losses only.

The pole face losses was calculated as follows:

$$P = 1.65 \times 10^{-7} K^2 \beta^2 \sqrt{\frac{\nu^3 \lambda}{\mu \rho}}$$

where

P = watts per square inch of pole face surface

K^2 = harmonic amplitude series; function of slot opening to air gap

β = average air gap flux density

ν = peripheral velocity of rotor

λ = tooth pitch

μ = permeability of pole face

ρ = resistivity of pole face

The calculated values of pole face losses for no-load and 150 KVA system operation are as shown in the following table below:

Generator Speed	Pole Face Losses-Watts	
	No-Load	150 KVA System
12,000 rpm	487	394
16,000 rpm	750	608
21,000 rpm	1128	914

4.2.1.2.3.2.3 I^2R Losses - The stator winding total I^2R losses for a converter output of 150 KVA is 4200 watts.

4.2.1.3 Generator Thermal Analysis

4.2.1.3.1 Thermal Analysis Description

A steady state thermal analysis, based on the thermal equivalent of Kirchoff's Current Law, is applied to a one inch long (axial) section of the center of the generator. Because of symmetry, only one half of a stator slot pitch width section (circumferentially) is required to perform this analysis. This axial section is analyzed by preparation of a network consisting of the thermal resistances that are connected at applicable thermal junctions (nodes). The nodes are temperature interest points with respect to the analysis. Factors considered in establishing the thermal resistances used in this network include conductivity of the materials and the type of fit of assemblies and parts. The thermal network is shown if Figure 49.

In this analysis, the losses are assumed to be concentrated at the nodes and the heat flow between the nodes to be radial and uni-directional. A pessimistic prediction of temperatures and the temperature distribution is expected from these assumptions are considered valid since heat flow to the cooling oil is short, direct and follows an excellent conduction path due to the rotor structure and materials used.

4.2.1.3.2 Thermal Analysis Results and Component Temperatures

The described analysis was conducted for no-load on the generator, and at 150 KVA loads on the system. The generator speeds used in this analysis were 12,000 RPM base speed, 16,000 RPM nominal speed, and 21,000 RPM maximum operating speed. The results of this analysis, shown with the generator losses in Table 1, show the predicted above-oil generator part temperatures.

4.2.1.3.3 Thermal Analysis Conclusions

Samples of the 300 maraging steel, shrink ring material, had been subjected to various temperatures with and without oil in an attempt to determine the surface temperature the rotor had experienced upon first noticing the surface discoloration on the magnetic portion of the shrink ring. These samples indicated a surface temperature between 230°C to 250°C had been experienced. The generator prior to being disassembled had been run up to a speed of 16,000 RPM and with oil temperature into the generator up to 90°C.

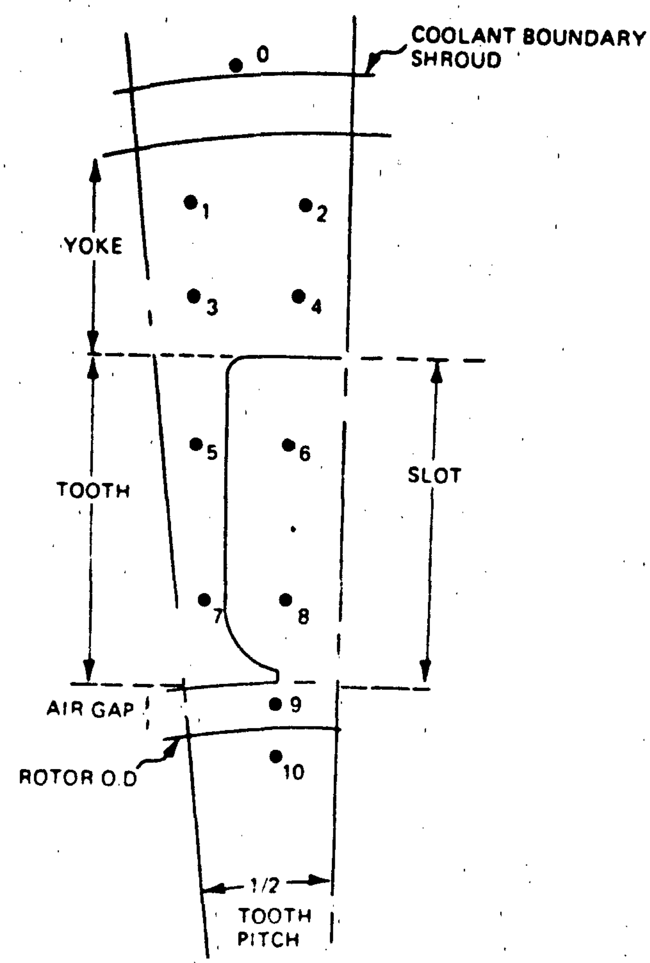


Figure 49. Thermal Network

TABLE 1
PREDICTED TEMPERATURES - GENERATOR THERMAL ANALYSIS

Thermal Circuit Node	Generator Location	Predicted Temperature Rise Above Cooling Oil					
		12,000 RPM		16,000 RPM		21,000 RPM	
		No-Load	150 KVA	No-Load	150 KVA	No-Load	150 KVA
1 & 2	Core	18	27	26	34	38	45
3 & 4	Core	27	43	39	54	58	69
5	Tooth	37	59	53	74	77	94
6	Slot	36	111	51	125	75	145
7	Tooth	42	66	59	82	86	105
8	Slot	47	137	66	154	95	179
9	Air Gap	93	122	127	154	178	199
10	Rotor Surface	102	130	141 *	165	200	216
Generator Location	Rotor Pole Face	487	394	750	608	1128	914
	Stator Core Tooth	986	767	1480	1315	2192	1863
	Stator Core Yoke	1629	1378	2506	2005	4010	3258
	Windage	1400	1400	1764	1764	2300	2300
Winding	I^2R	-0-	4200	-0-	4200	-0-	4200
Total Losses		4502	8139	6500	9982	9630	12,535

* See text below.

It is interesting to note that the thermal analysis predicts a rotor surface temperature rise of 141°C above cooling oil for 16,000 RPM at no load as indicated in Table 1. This would be 231°C for 90°C cooling oil which corresponds with the test conditions where surface discoloration indicated a temperature of 230°C to 250°C.

After the first machine failure, the stator was equipped with thermocouples in the generator air gap region at the approximate center of the stack. Upon starting of the no-load generator testing with the new stator, it was again subjected to 16,000 RPM and 90°C cooling oil into the generator. The generator was disassembled after this to examine the discoloration on the rotor surface which would indicate the maximum temperature experienced on the rotor surface. Again the surface discolorated to indicate a temperature between 230°C-250°C. This correlated very well with the air gap thermocouples in accordance with the thermal analysis, using the lower stator tooth thermal node #7, Figure 49.

The temperature differential from the slot to the rotor surface at no-load was calculated to be +75°C at 16,000 RPM. The recorded slot temperature with 90°C oil in at 16,000 RPM was 152°C so the predicted rotor surface temperature would be 227°C (152°C measured slot temp +75°C predicted differential).

Based on the correlation between the thermal analysis, shown in Table 1, and the thermal couple measurement, it is concluded that the thermal analysis results can be used to predict with reasonable accuracy the rotor surface temperature which appears to be a critical area as shown in Figure 50. To prevent the possibility of irreversible demagnetization losses in the rotor magnets, operation limits were imposed on the generator. With 60°C cooling oil and rated 150 KVA system load the maximum generator speed is 18,000 RPM. Operation above rated load was limited to short duration runs at a maximum of 15,000 RPM

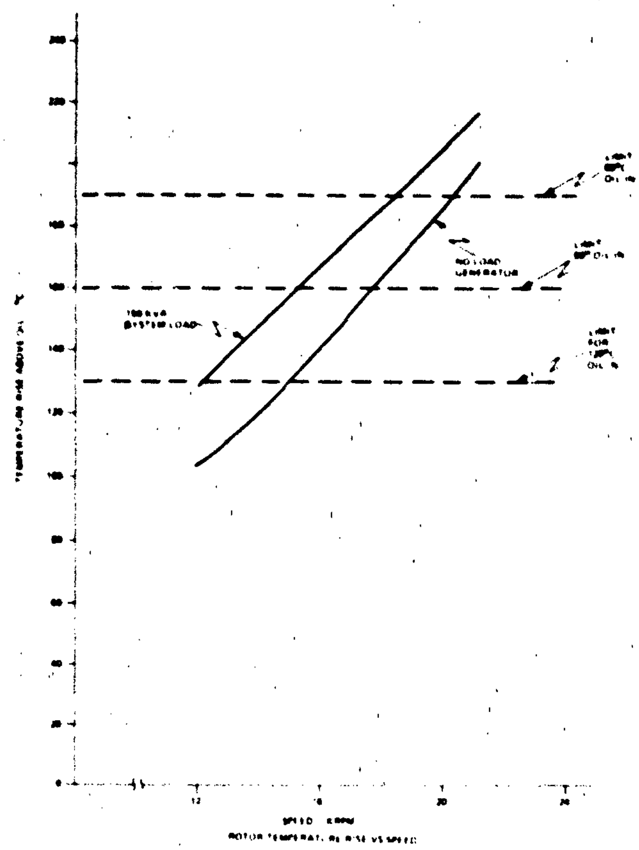


Figure 50. Rotor Temperature Rise vs Speed

The reason for the thermal problem is in large part due to the pole face losses.

The pole face losses are minimal with a closed stator slot and large air gap but the commutating reactance is high. This combined configuration is not practical, however, since flux is required in the air gap to generate output and an open slot readily permits insertion of coils. The pole face losses can be reduced by laminating the magnetic members of the shrink ring composite at the rotor surface or by laminating the shrink ring composite and applying a high resistance coating between the laminations. However, laminated configurations are not practical for high speed rotors because they have inadequate strength.

The slot opening to air-gap for this permanent-magnet generator design was optimized to achieve minimum commutating reactance and pole face losses. At 16,000 RPM the pole face loss was calculated to be 700 watts and was verified on a loss breakdown type test. Although this loss might normally be considered insignificant, when compared to a total generator output of 210 KVA at full load, the heating is significant because these losses cannot be removed from the rotor except by means of a thermal path across the air gap and through the stator to the cooling oil. Therefore, rotor temperatures must inherently be higher than the stator slot temperature.

4.3 CYCLOCONVERTER

4.3.1 CYCLOCONVERTER PHYSICAL DESCRIPTION

The cycloconverter 3S2060DF139A1 is housed in an aluminum alloy enclosure occupying approximately 5.5 cubic ft, nominal dimensions 12.5" high x 18.5" wide by 41.3" long and weighing approximately 211 lbs (dry weight). Figure 51 provides installation dimensions. All interface connections are made from a single face of the enclosure as indicated. Removal of side covers provides access to the four .53 dia mounting holes. Provisions for handling the cycloconverter are included with recessed handles on the two long sides of the enclosure.

Figures 52 thru 62 are photographs of the cycloconverter. Figures 52 and 53 are outside views with covers on. After these photos were taken, it was found necessary to add two small blowers to sufficiently cool the interphase transformers (IPT's T1-T18). Figure 53 illustrates this modification (a similar fan and vent are included on the opposite side).

Figure 55, with top and left side covers removed show the location of the IPT's and SCR firing circuits and the despiker resistor bank (R40-48, 73-152). Figure 56 illustrates the similar arrangement of the IPT's and SCR firing circuits on the opposite side. Also note location of plug in logic boards.

Figure 57 is a bottom view with the cover removed showing a portion of the output filter capacitors, subassembly A8, and CT12.

Figure 58, top view, shows location of contactor K1, subassembly A7, and illustrates the wiring to the input power connectors, and shows details of the swivel fittings and oil coolant hose connections to the despiker resistor bank.

Figure 59 illustrates access to the SCR bank (Q1-Q54) by raising the despiker resistor plate. Figure 60 is a close up view of the SCR bank and shows the location of the despiker capacitors (C1-C9).

Figure 61 shows the power supply extended for servicing.

Figure 62 illustrates a typical plug-in double sided printed wiring logic board. There are, in the design, 23 printed wiring boards (13 types) of which 14 are plug-in type for ease of maintenance.

4.3.2 CYCLOCONVERTER DESIGN DETAILS

All power connections between the cycloconverter and the generator are made through interconnection cables terminating at connectors J1 through J6 (see Figure 51). Connector J7 provides for necessary control connections between the generator and the converter, while provisions are made at connectors J8 and J9 for system control and test readouts. Output power connections are made at the MS27212-5-4 terminal board. Provisions for connecting the oil coolant supply are also included on the end of the cycloconverter enclosure.

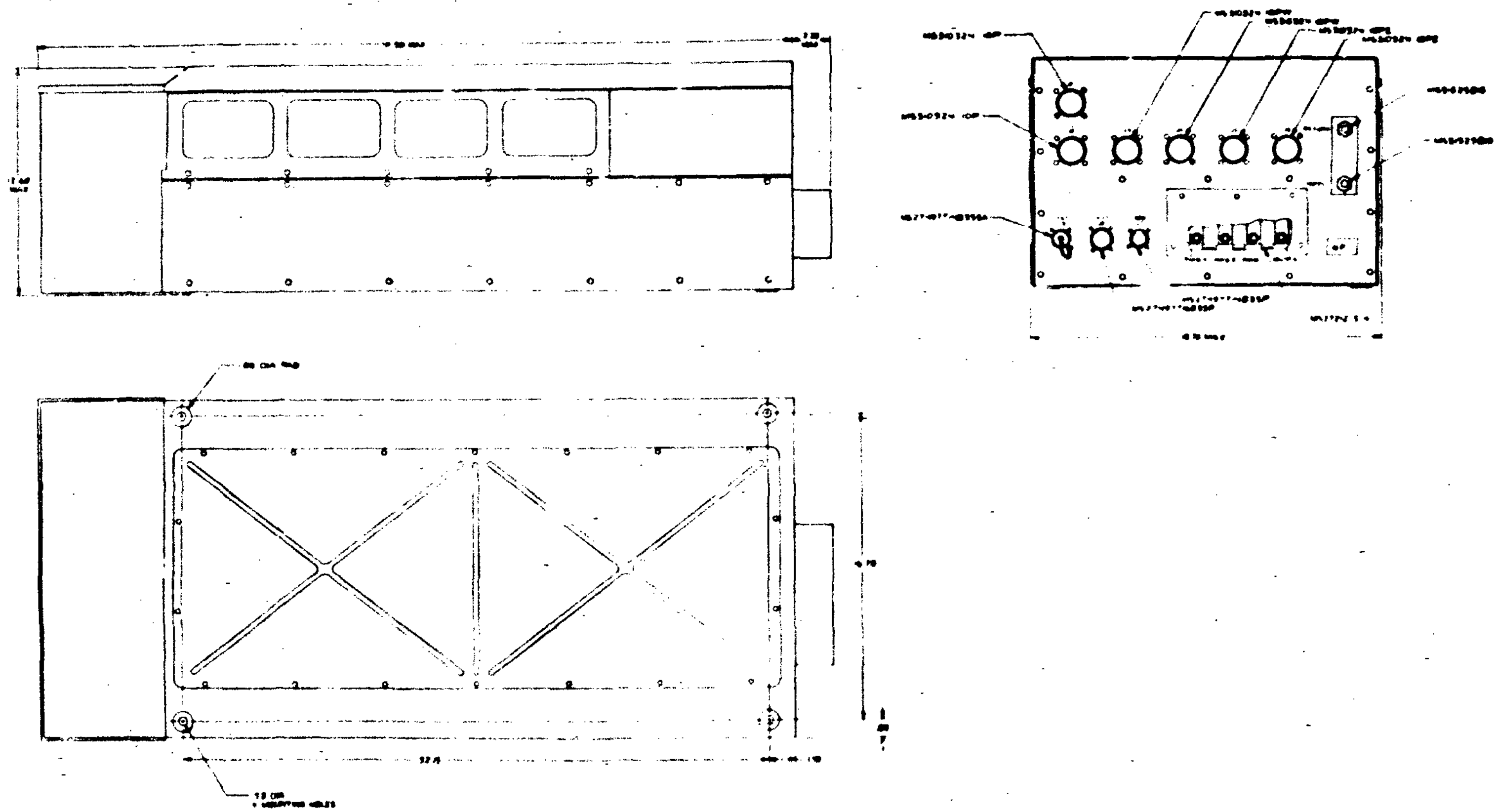


Figure 51. Cycloconverter Installation Control

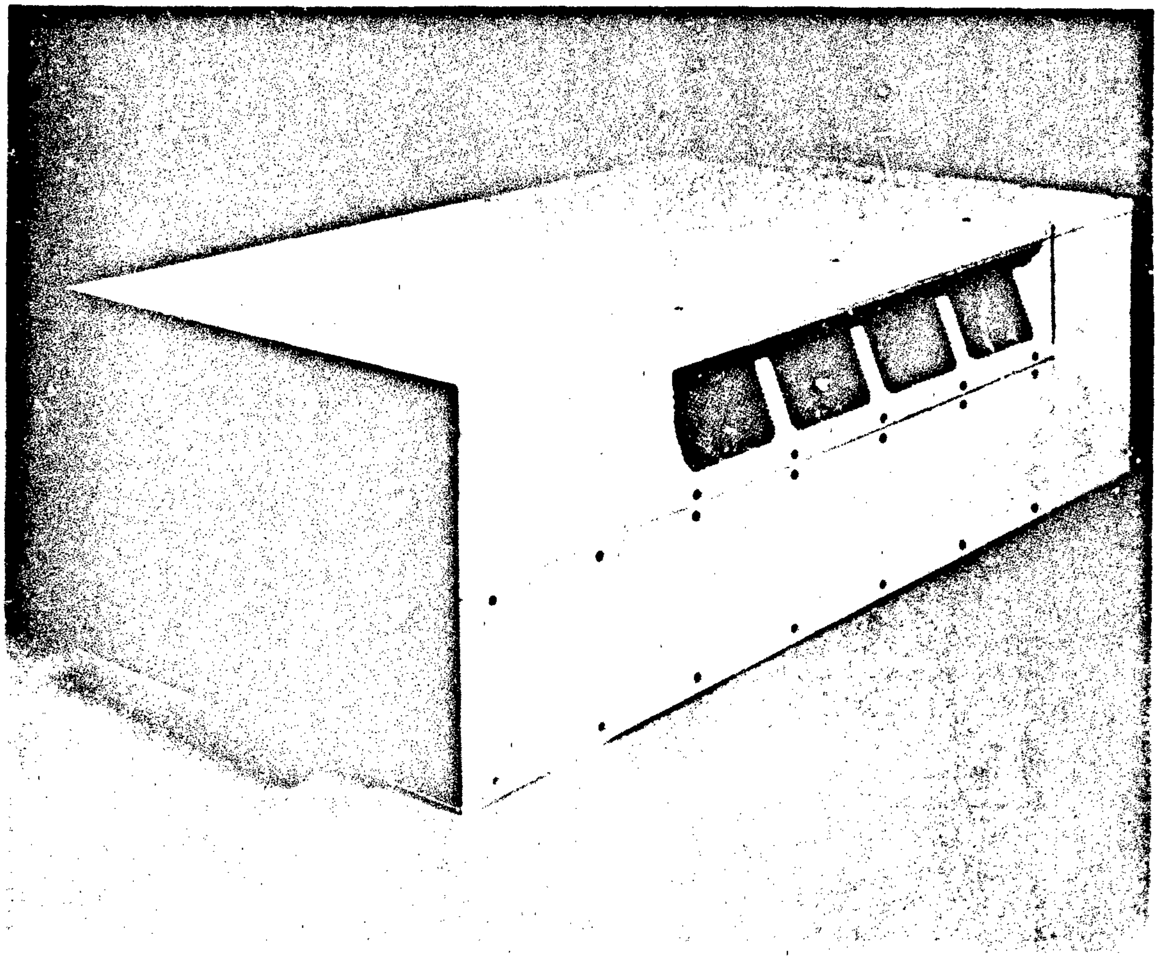


Figure 52. Outside View-Cycloconverter Covers in Place

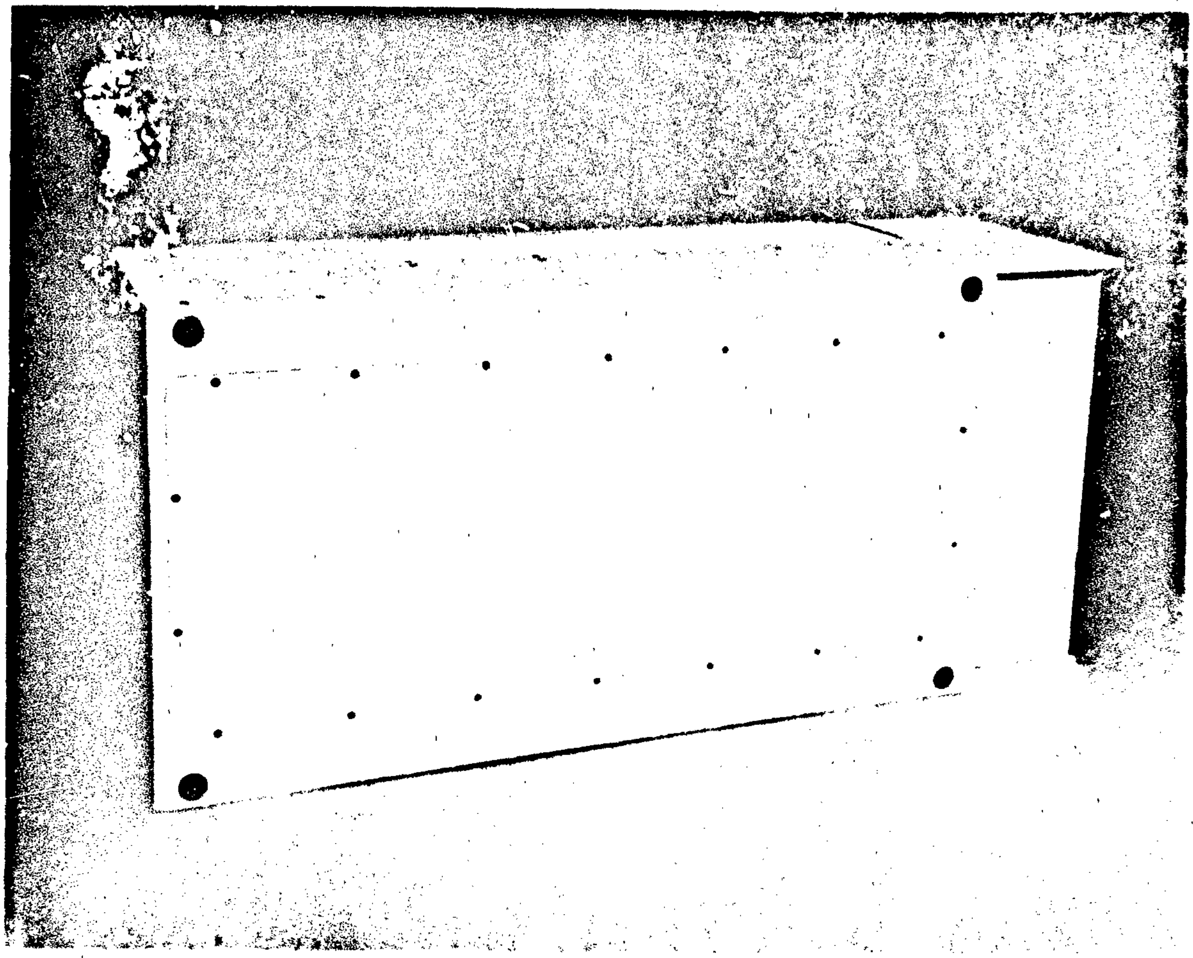


Figure 53. Bottom View-Cycloconverter Cover in Place

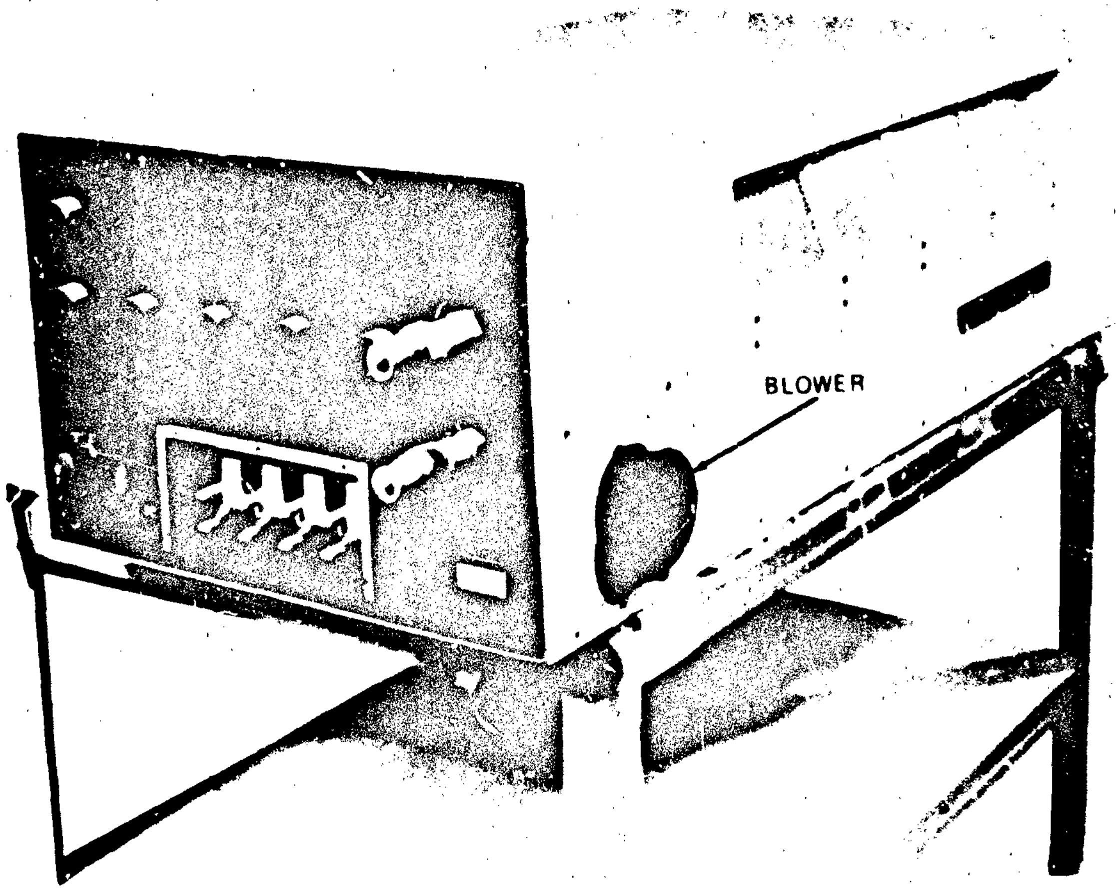


Figure 54. Cycloconverter Showing Blower Modification

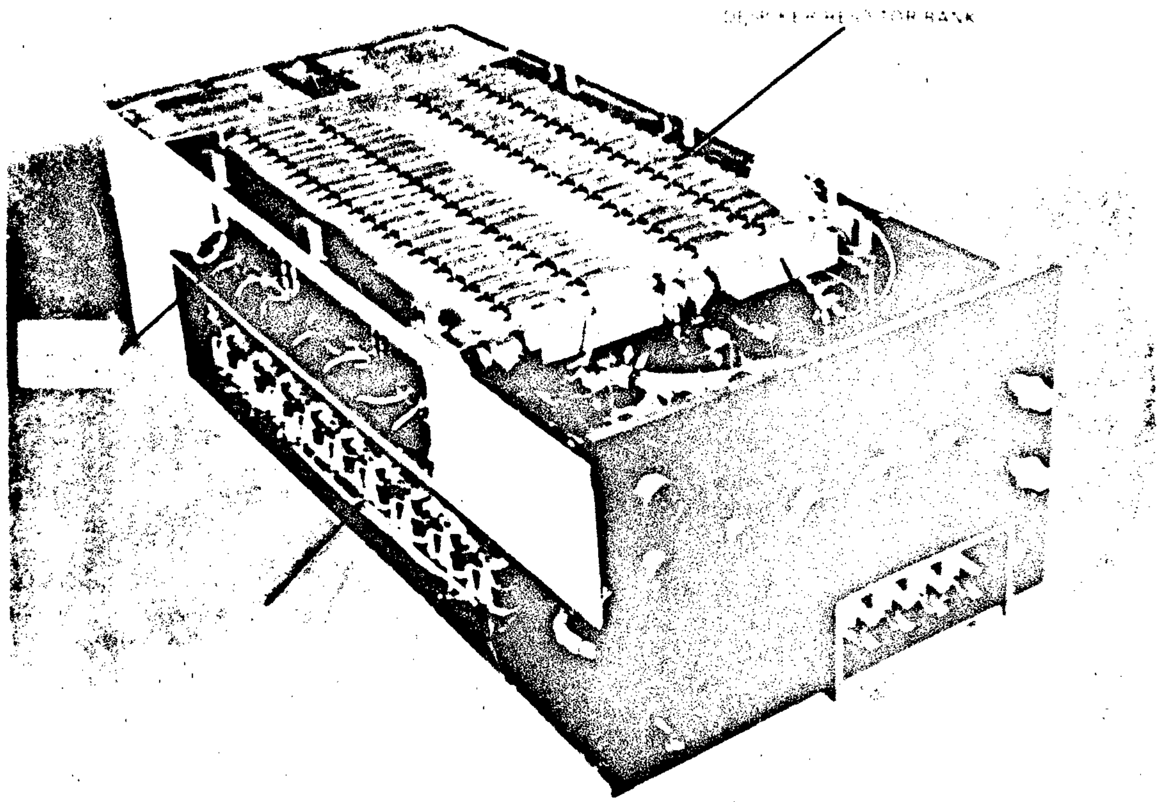


Figure 55. Left Side-Cycloconverter Covers Removed

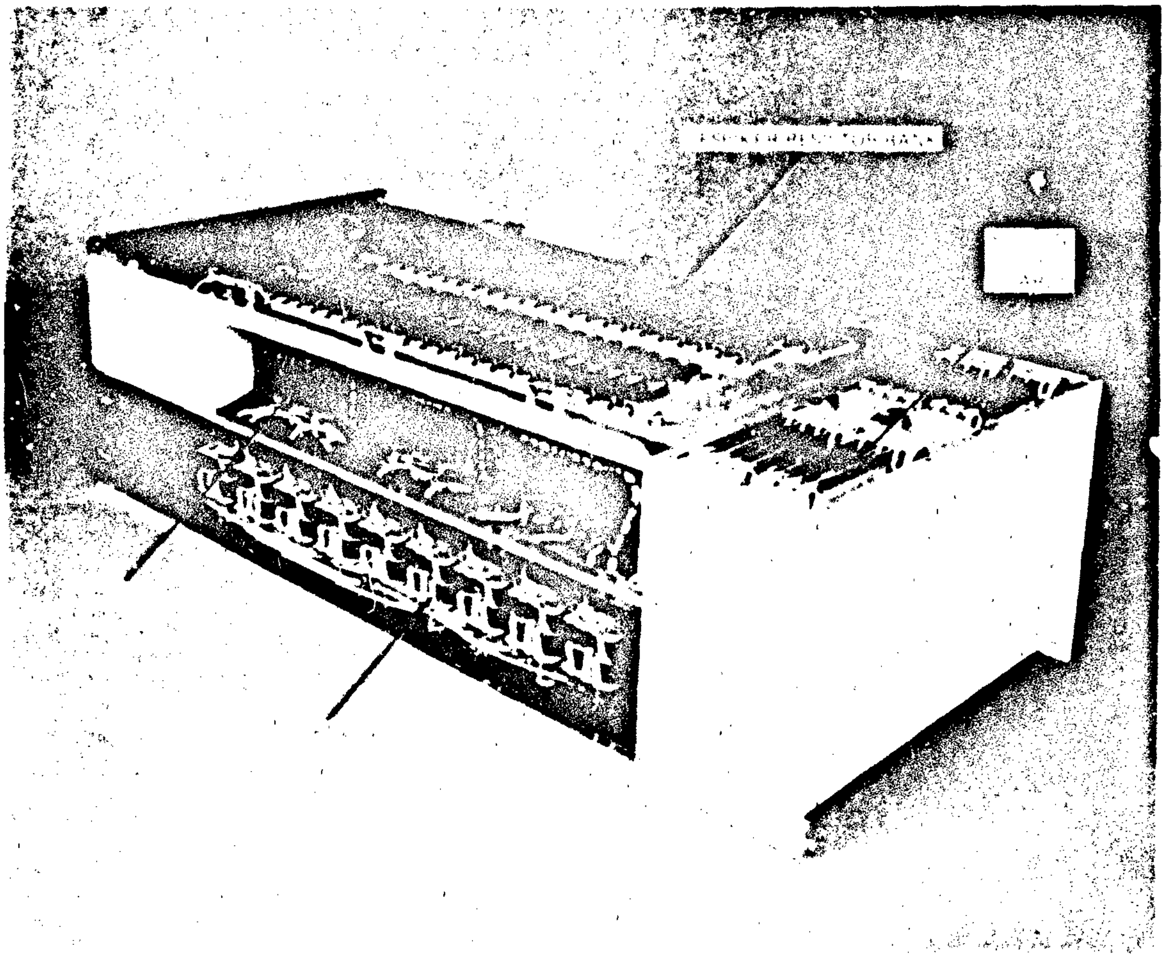


Figure 56. Right Side-Cycloconverter Covers Removed

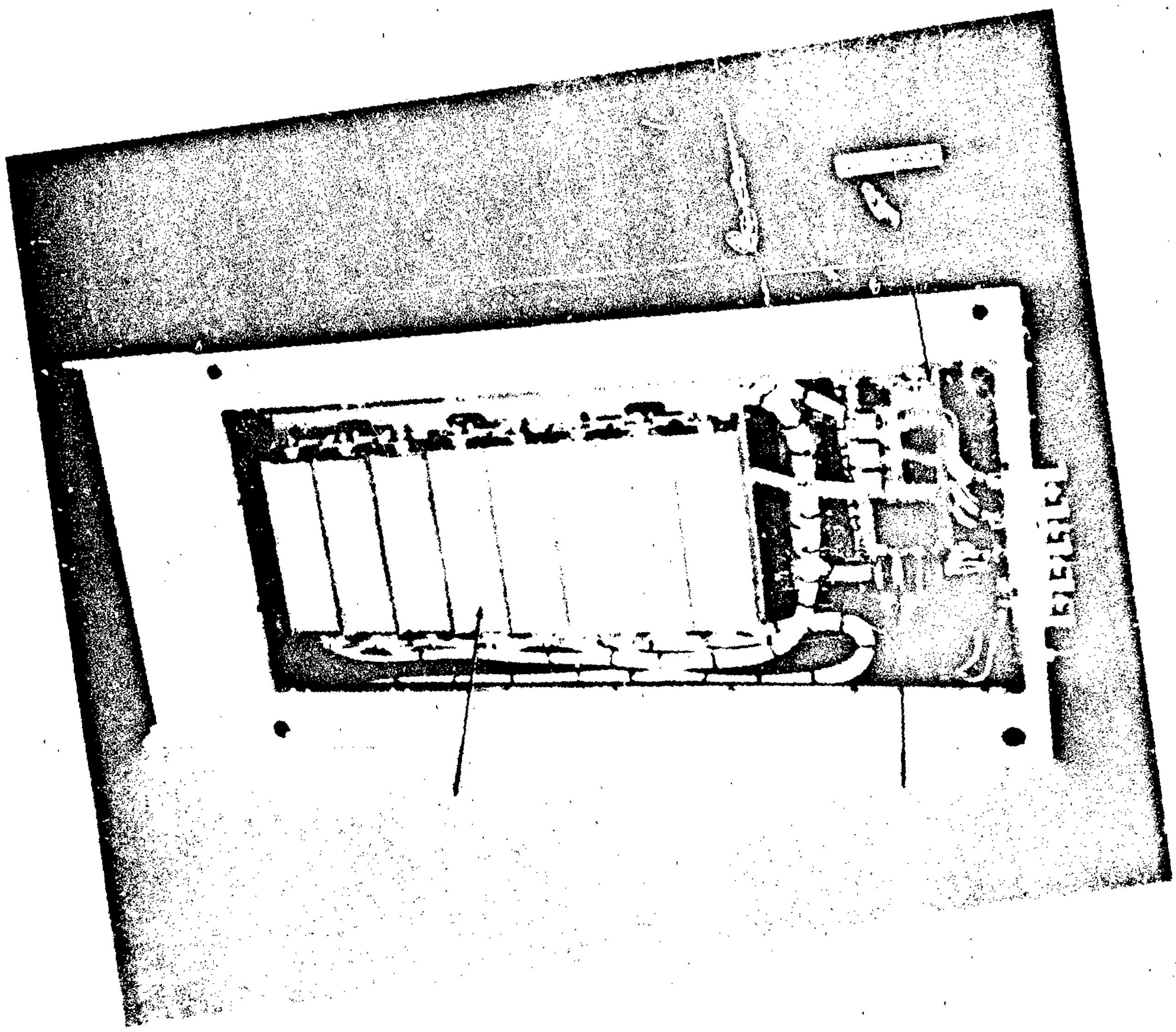


Figure 57. Bottom View-Cycloconverter Cover Removed

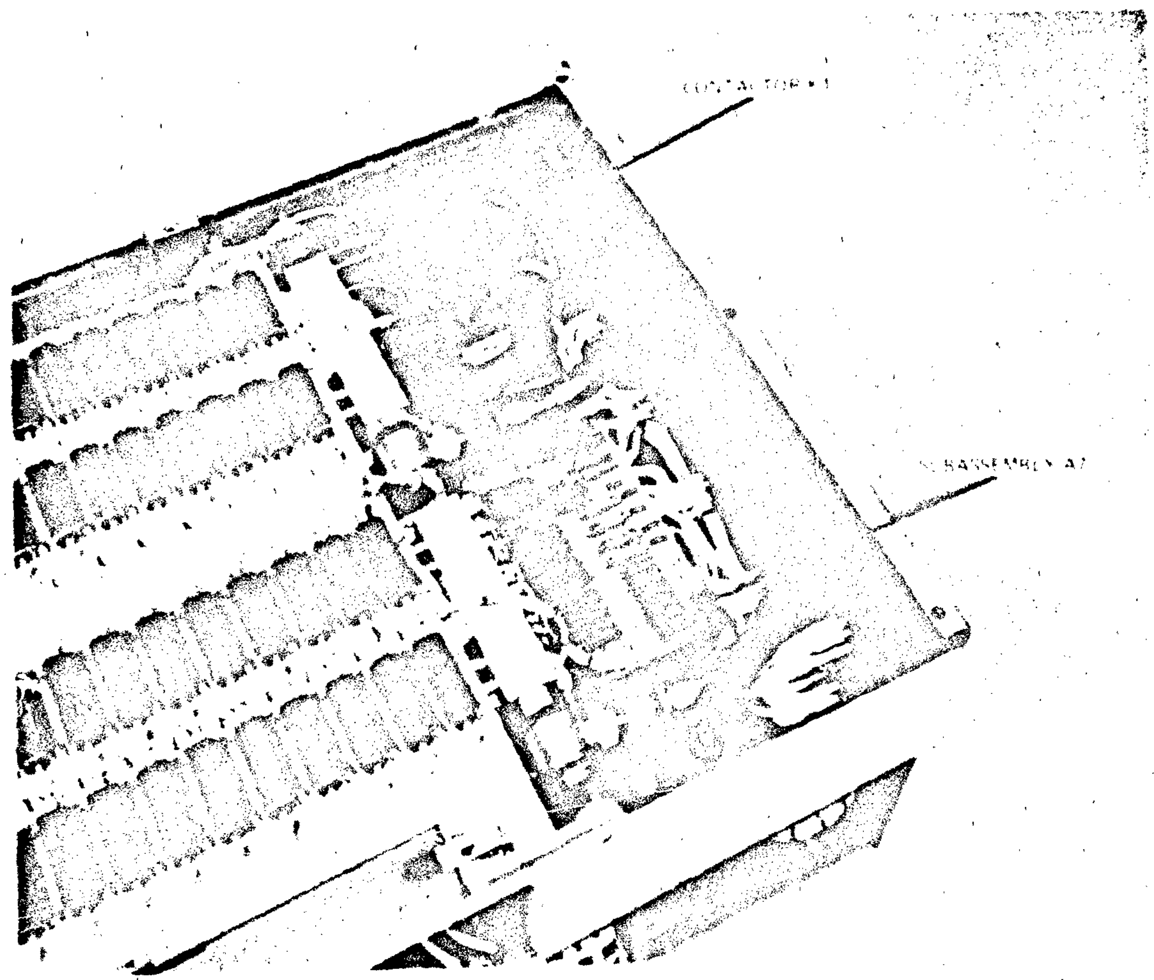


Figure 58. Top View Contactor End-Cycloconverter

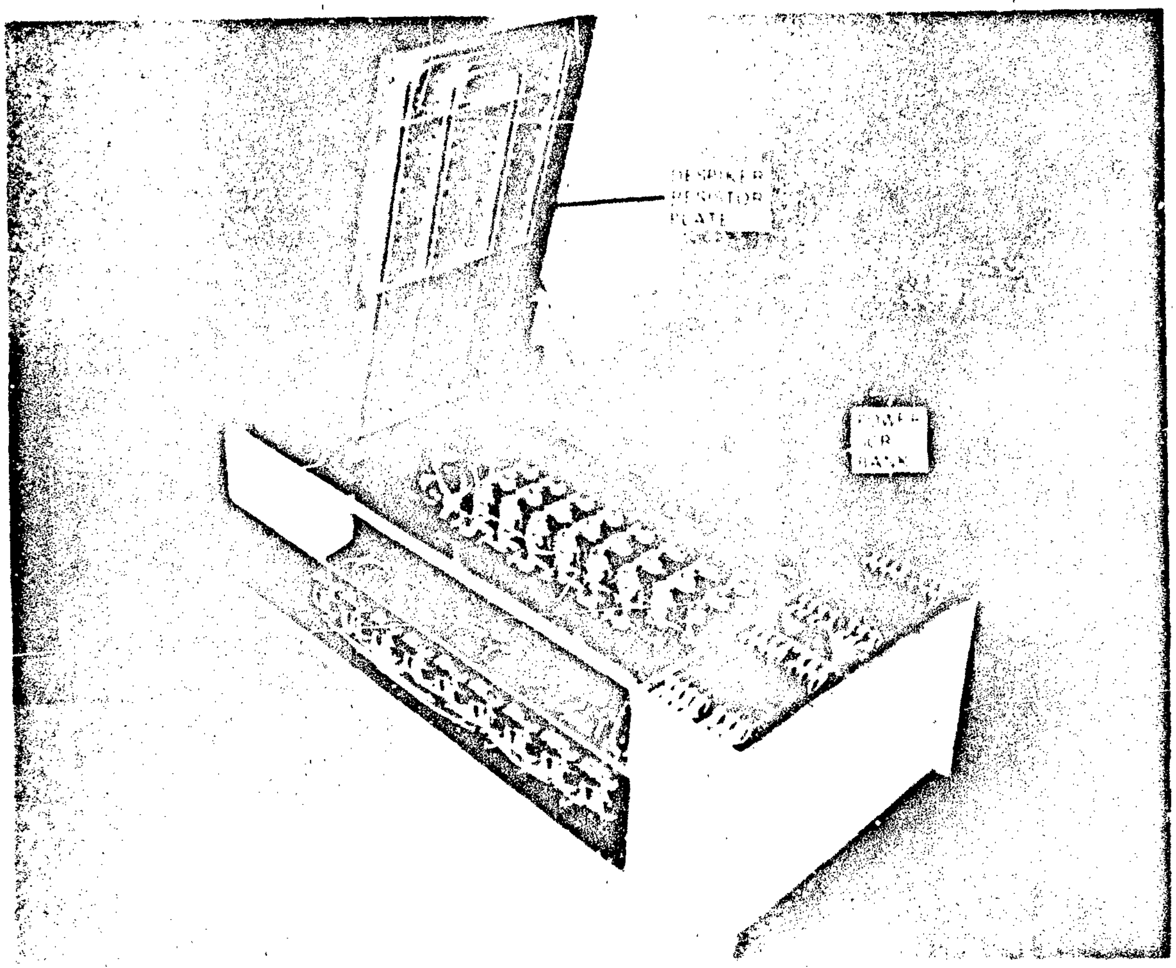


Figure 59. Top View-Cycloconverter, Showing SCR Bank

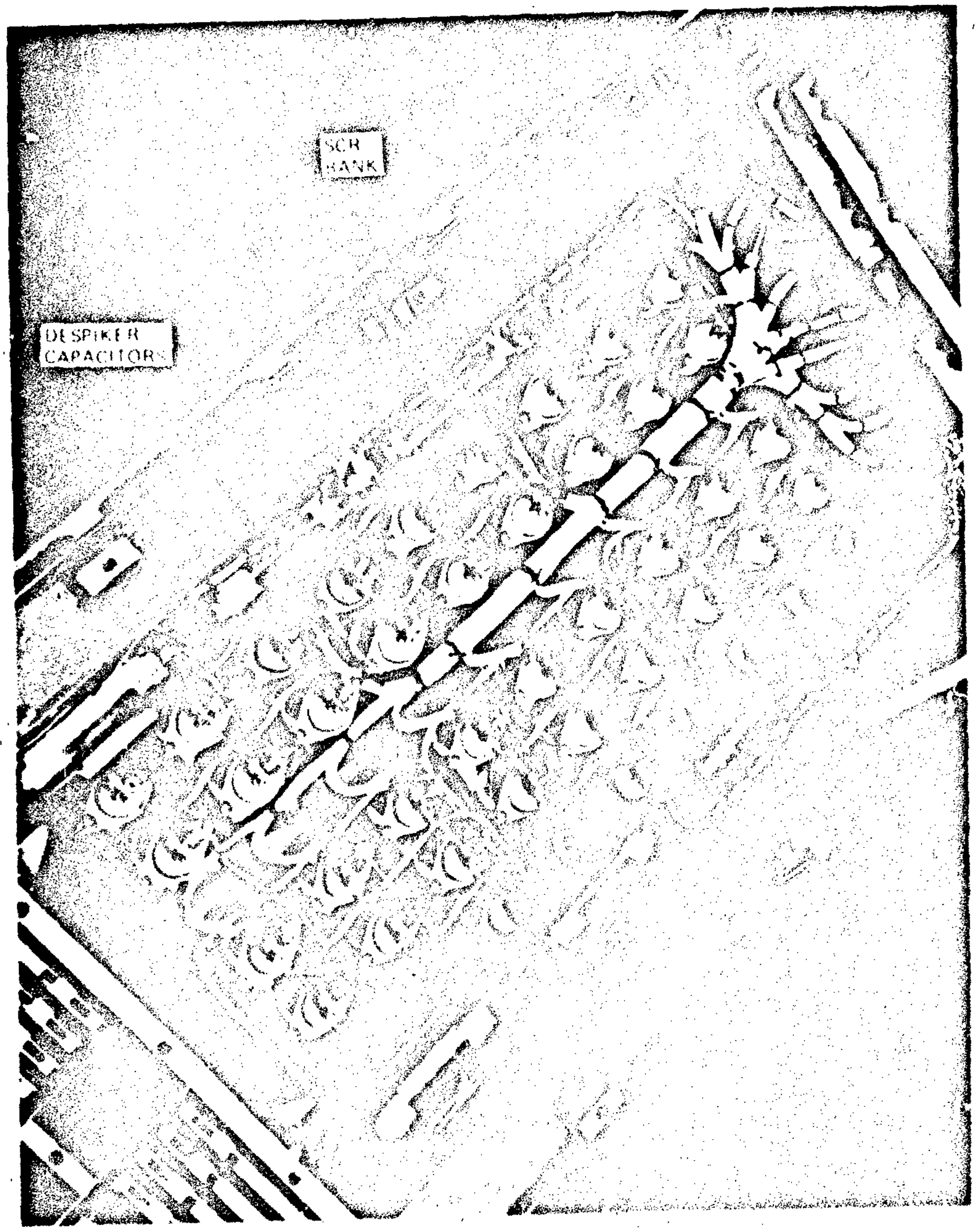


Figure 60. Cycloconverter, Close-Up SCR Bank

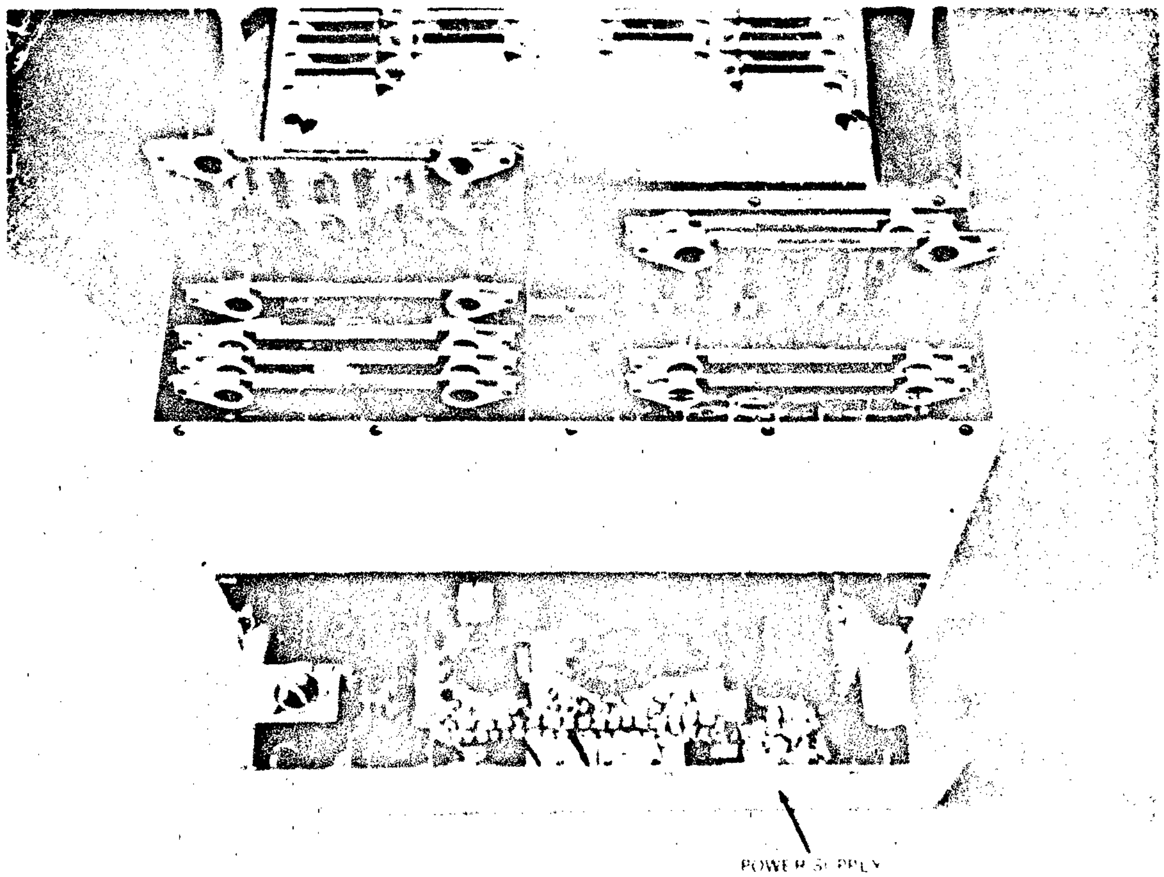


Figure 61. End View-Cycloconverter

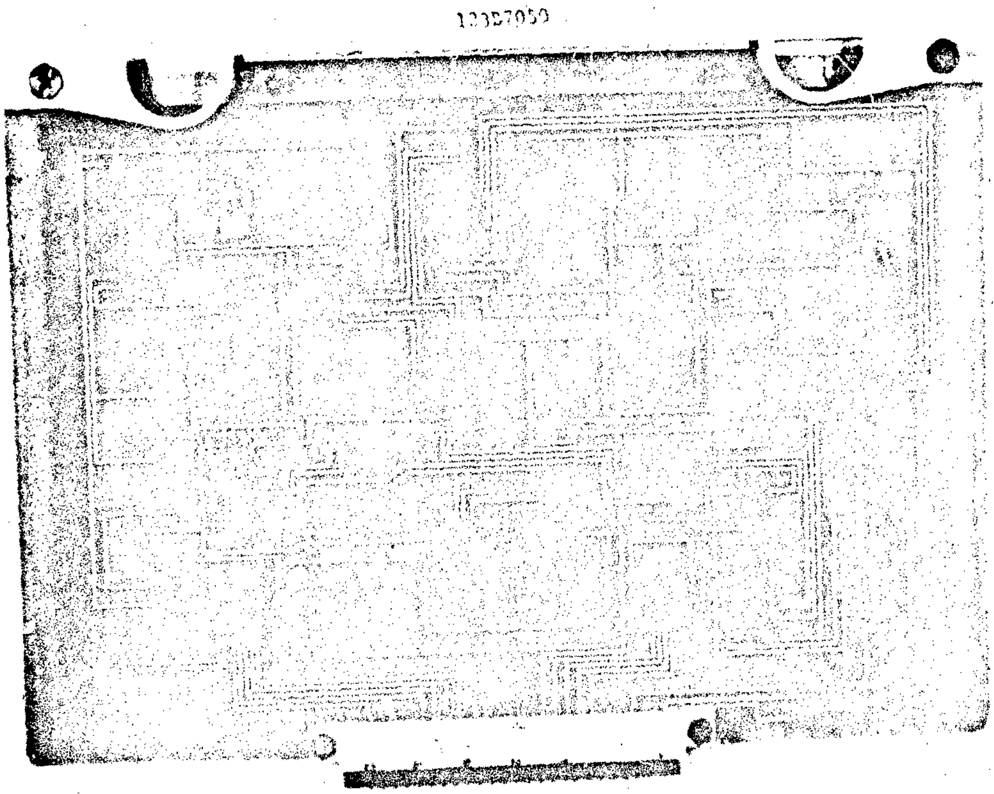


Figure 62. Typical Plug-In Logic Board-Cycloconverter

Particular attention has been paid throughout the design to observe good engineering design practices. Accessibility for test and parts replacement was a consideration during all phases of the design development.

Thermal considerations were of primary interest. Because of the large amount of heat to be dissipated by the cycloconverter (7 KW at rated output load) the use of forced air cooling posed several problems:

a) Heating of the space utilized for test and/or demonstration of the system.

b) Ventilation of the test area as a result of a) above

c) Fan noise

d) The effect of air ducting requirements on the volume of the enclosure.

Agreement was reached to provide a liquid cooled design and thermal studies conducted indicated preference for a closed loop oil cooled (Mil-L-23699 Engine Lube Oil) design with an external oil-to-water heat exchanger.

Many coolant flow and component part layout configurations were considered. The final design was based on necessary compromises involving evaluation of:

- cooling efficiency
- component dissipation levels and temperature ratings
- component accessibility
- requirements for electrical layout and wire routing
- cooling layout simplicity
- finished appearance
- volume objectives

Optimum thermal efficiency in applying the power SCR's was a prime consideration in the design. The method utilized mounts the SCR's to a "cold" plate by means of a spring loaded clamping arrangement. The SCR (see 153C6836G1 Figure 63) is insulated electrically from the chassis with a Beryllium Oxide disc coated with thermal grease to reduce interface thermal resistance. This method provides a large area of contact with the cooling surface and good contact pressure for low thermal resistance, while at the same time permitting component replacement without requiring access to the back of the cold plate (such as is required when using conventional stud mounted devices). Simplification of cold plate design is also achieved.

The use of a basically conventional SCR with the stud removed creates a problem in making an electrical connection to the anode (particularly since electrical isolation from the chassis heat sink is required). Since the existing hexagonal shaped sides of the SCR are steel, no efficient power connection is possible at that interface.

The problem was resolved by modifying the SCR with the addition of a plated copper disc with a tab (for electrical connection) between the anode face and the BEO insulating disc. To keep interface thermal losses to a minimum and to provide mechanical positioning for the electrical connection, the copper disc was soldered to the anode face of the SCR as indicated in Figure 63. A low melting temperature solder (293°F) was used in the process developed for making this modification. Preheating the SCR and the tab in a holding fixture, and the use of a temperature controlled soldering iron for applying solder to the SCR prior to assembly was required to achieve an essentially void free interface. Figure 64 is a cross section of the SCR assembly.

The process described above for modifying the SCR, while satisfactory for developmental work, requires considerable hand labor. Addition of a provision for suitable electrical connection by the SCR manufacturer would be desirable for production runs.

Predicted thermal losses in the IPT's (interphase transformers) also required special consideration in design. Each IPT is encapsulated in an individual aluminum alloy casting which in turn is bolted to a "cold" plate. Early tests revealed excessive losses and it was found necessary to provide numerous small slots in the bottom of the casting to reduce eddy current losses brought about from leakage flux. As previously mentioned in this discussion, final test evaluation indicated the IPT temperatures were still excessive with the oil cooling means provided and two small blowers were added as shown in Figure 54.

4.3.3 CYCLOCONVERTER THERMAL CONSIDERATIONS

The cooling design of the cycloconverter was based on the predicted losses shown in Table 2. A maximum input oil temperature of 70°C and a five gallon per minute flow rate was assumed in making thermal predictions. Because of the operating temperature limitations of the power SCR's, the oil was used first to cool these devices so they would "see" the lowest coolant temperature. As noted in Table 1 the interphase transformers and despiker resistors were the other primary power dissipation contributors, and thus required oil cooling. Natural convection and conduction cooling was used to dissipate the losses generated in the remaining circuit elements.

The oil coolant path developed as a result of thermal analysis and considering other aspects of the design as discussed in Section 4.3.2 is shown in Figure 65. Prediction of expected pressure drops throughout the piping system were used to determine piping and fitting sizes to stay within reasonable design limits for pressure build-up at the flow rate desired (5 gallons per minute). These predictions were used to determine the pressure test required on the cycloconverter coolant system prior to assembly. A pressure drop of approximately 40 psi at 5 gallons per minute was predicted for the complete system.

The main chassis was fabricated by a combination of welding and dip brazing. The coolant system components were welded first. All access holes to the coolant system were then plugged and the complete assemblage dip brazed. The first dip brazing operation was partially unsuccessful in the area of bonding the SCR cooling tubes to the heat sink. A second dip improved the bonding in this area but created two problems:

1. Leaks in the cooling system (tubes cracked).
2. Distortion of the chassis, requiring extensive repair work.

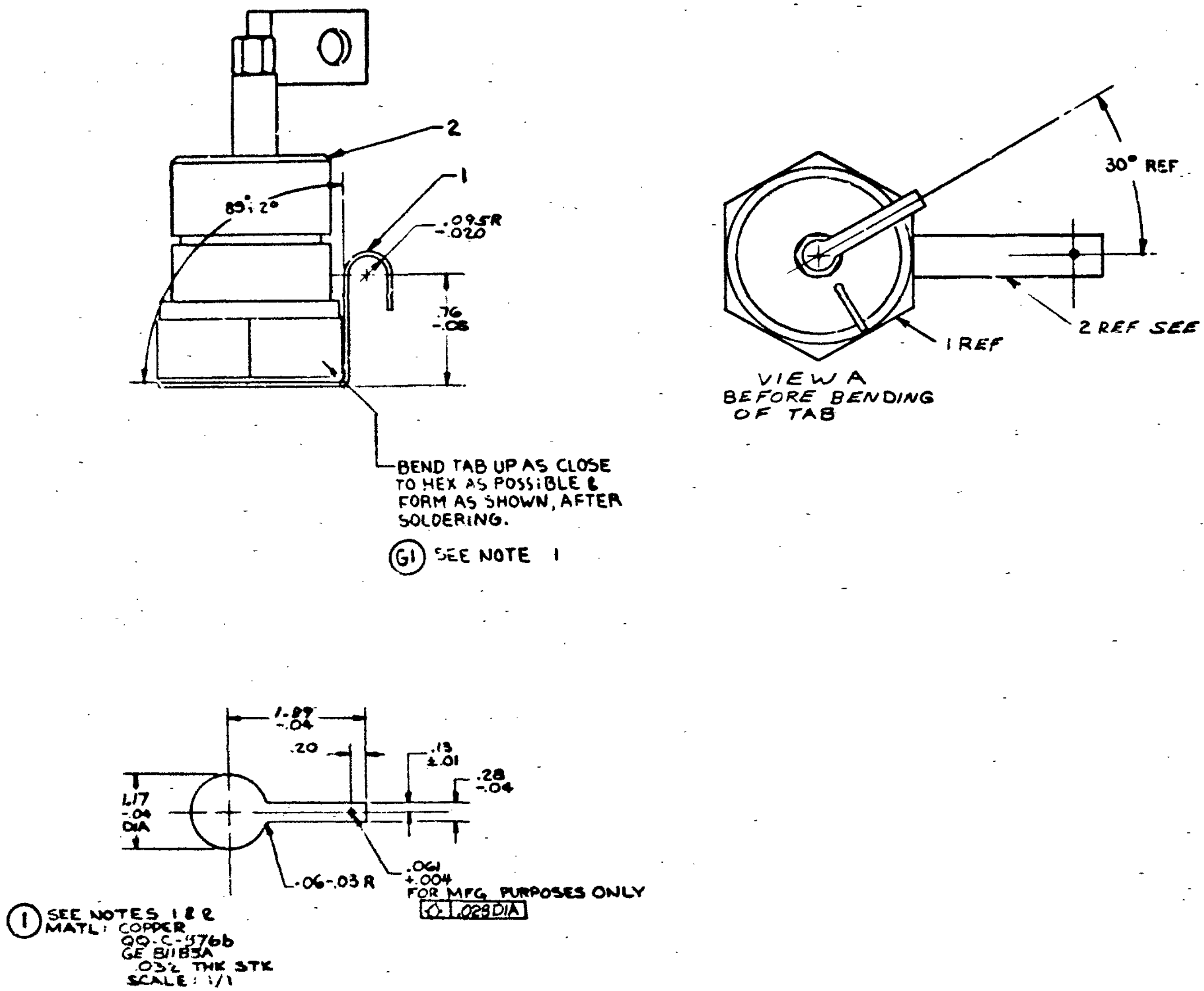


Figure 63. Silicon Control Rectifier Assembly

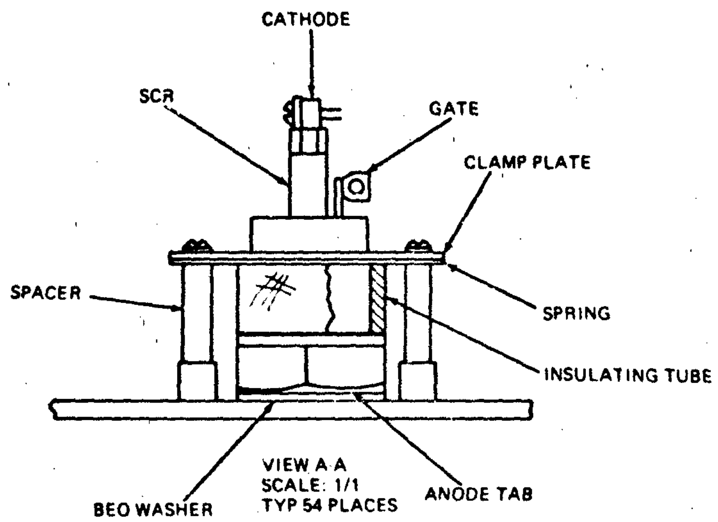


Figure 64. Cross Section of SCR Assembly Method

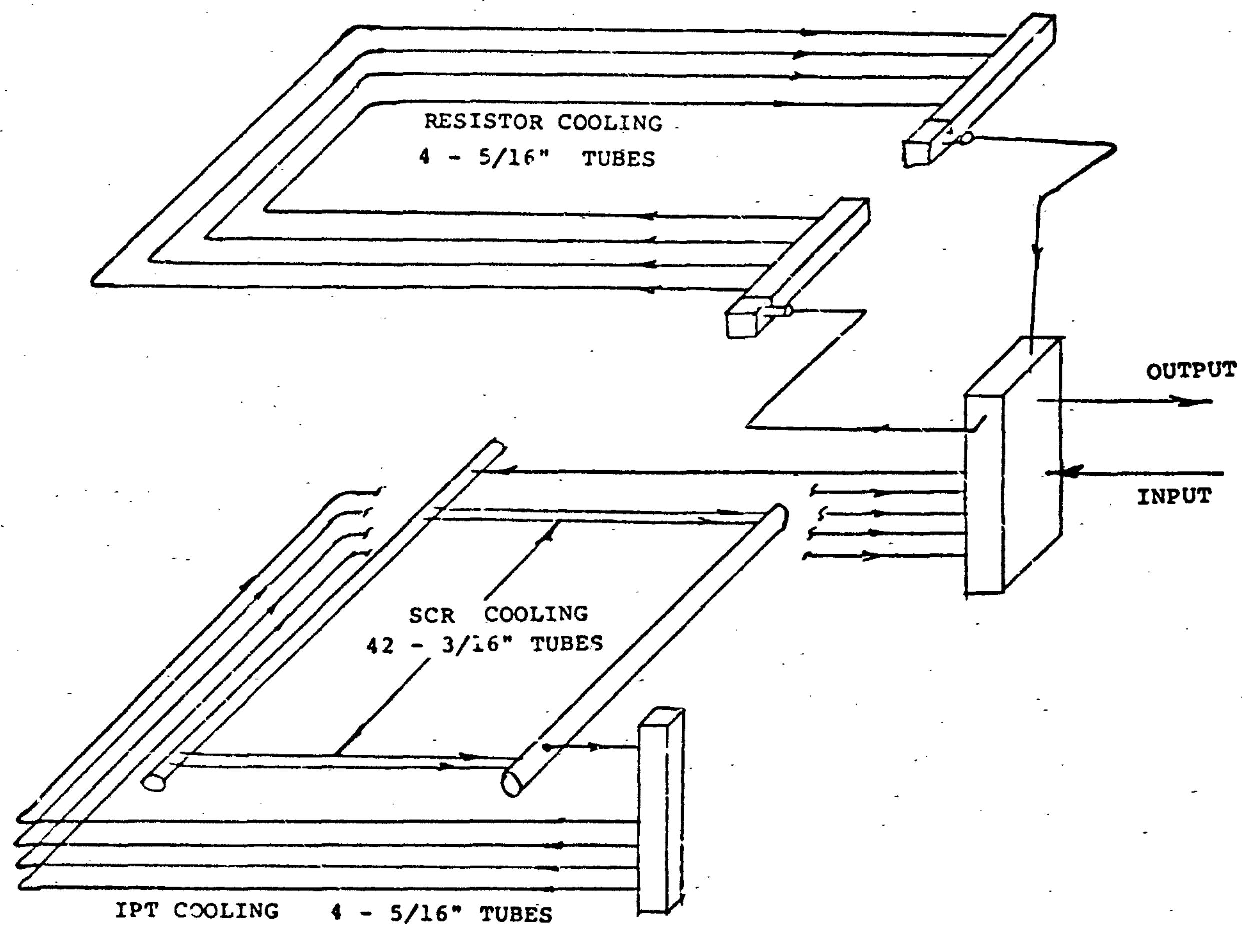


Figure 65. Cycloconverter Oil Coolant Piping

TABLE 2

PREDICTED LOSSES (WATTS)

	Full Load	No Load	5 Min. Overload	5 Sec. Fault
54 SCR's	2500	800	4250	175/200 Watts per SCR*
18 Interphase Transf.				
Iron	180	250	120	
Copper	1260	113	2835	
Induction	400	100	600	
90 Despiker Resistors	2000	4500	1700	
15 Filter Capacitors	125	125	125	
9 Despiker Capacitors	50	90	70	
Wiring	250	50	560	
Pulse Transf. Network	35	35	35	
Power Supply	40	40	40	
Printed Wiring Bds.	25	25	25	
Misc. Control	50	20	100	
Total	6915	5348	10460	
*Up to 2/3 of SCR's affected.				

Efforts to repair the leaks in the cooling system by welding were only partially successful; complete sealing was achieved by applying a vacuum to the piping system and brushing on a permafil sealant in the trouble areas. To improve the thermal resistance between the SCR coolant piping and the "cold" plate, this area was encapsulated with a high thermal conductivity epoxy. Figures 66 and 67 show details of the piping and the encapsulated area.

Based on the experience gained in designing and constructing the main chassis, several improvements in design and procedures should be considered in the future.

a) Tubing should be annealed after forming and should be purchased in a T4 temper.

b) In welding tubing to heavy sections (such as a manifold) the heavy section should be machined so to provide a section of approximately the same thickness as the tubing to equalize heating at the weld and to provide for stress relief.

c) Repair of bad brazed joints by welding is difficult because of the alloys formed as a result of the dip brazing process. A brazing alloy and torch would be better.

d) Consideration should be given to using smaller dip brazed assemblies then join by torch brazing or with mechanical joints.

e) Holes in aluminum tubing might be brought about as a result of non-metallic inclusions. Minimize by using refrigerator grade extruded stock.

f) In welding tubes a preformed ring of filler wire might be helpful.

g) Investigate use of "D" shape tubing flared at ends to weld to header to secure better heat transfer to cold plate.

h) Use of clad material in dip brazing is desirable.

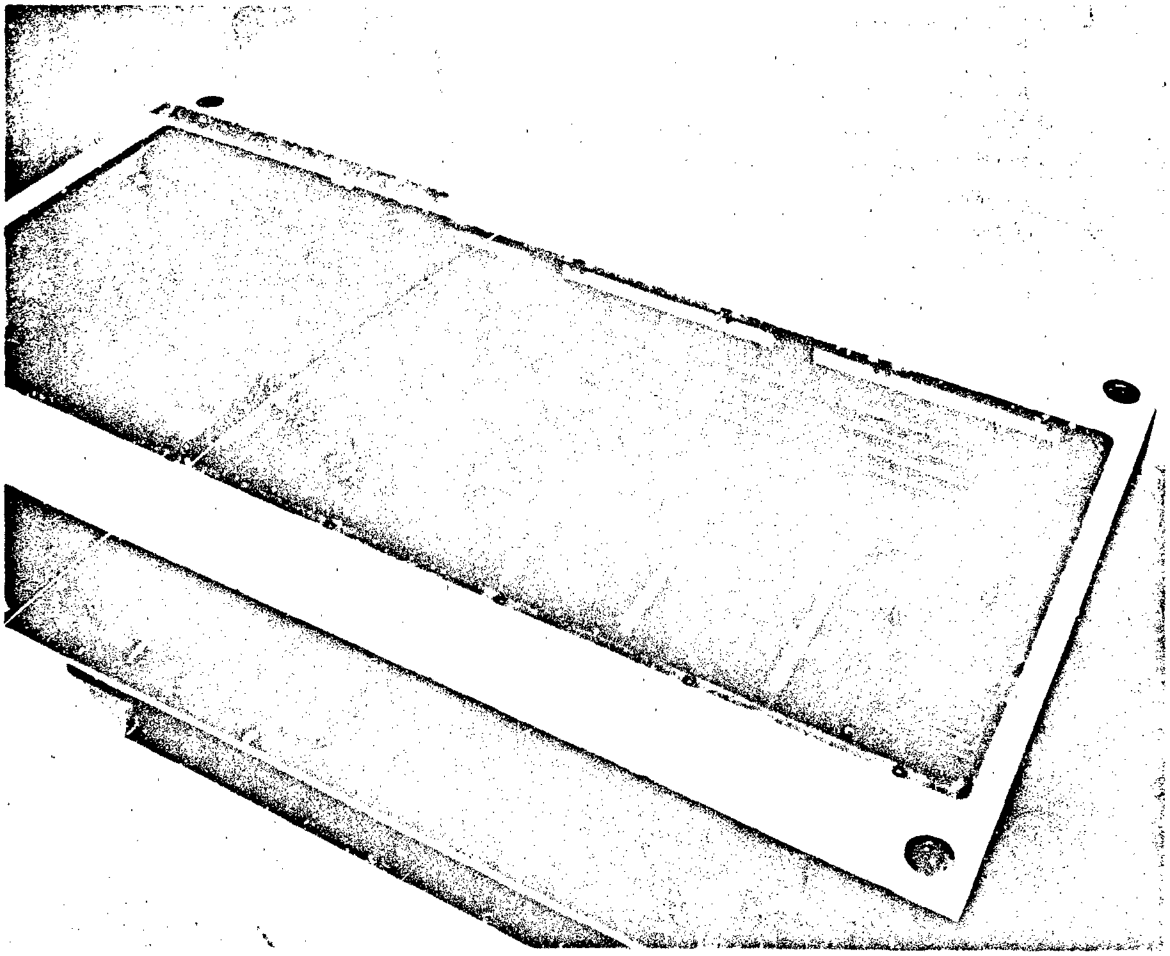


Figure 66. Main Chassis Before Assembly View 1

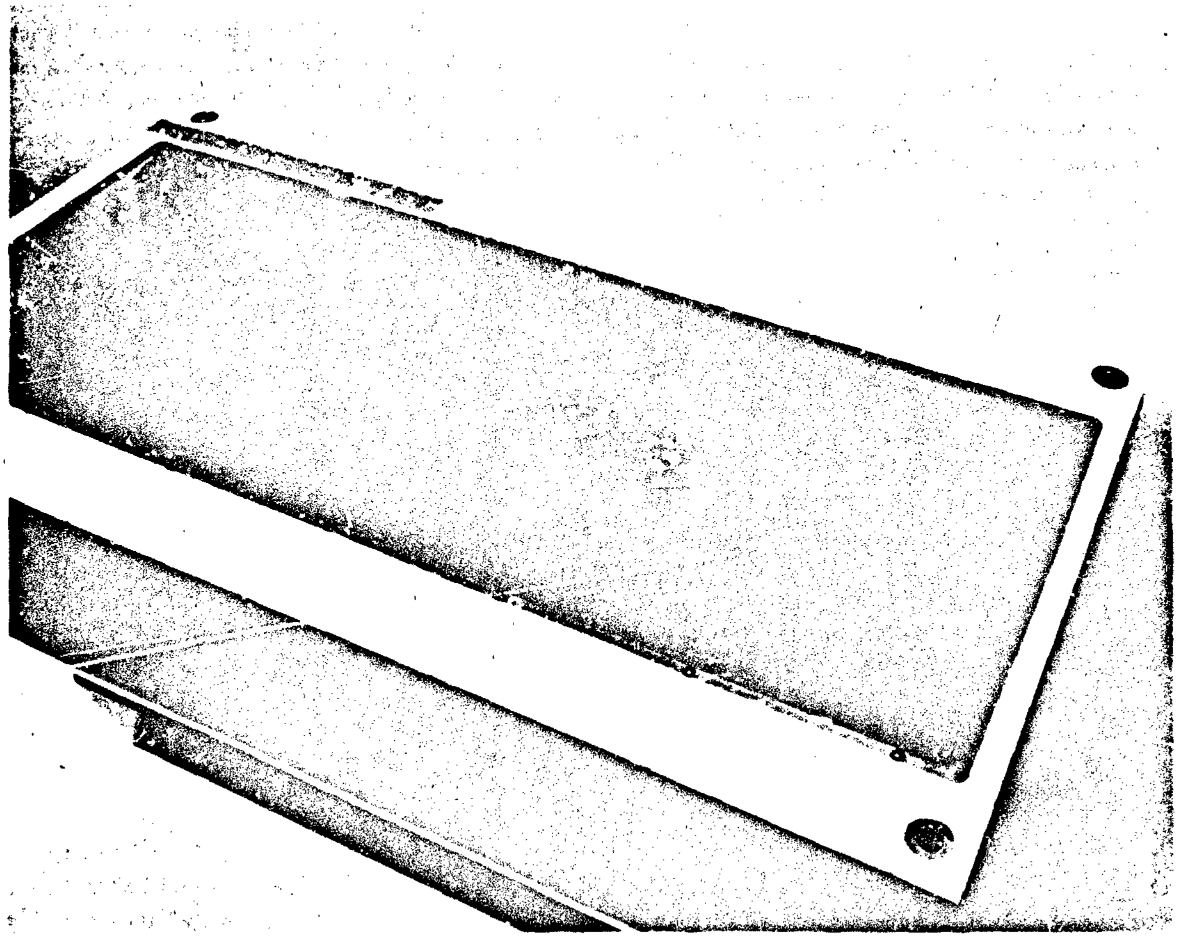


Figure 67. Main Chassis Before Assembly View 2

SECTION V

TWO CATASTROPHIC FAILURES IN TEST

5.1 GENERAL

Failures in test during any development program are not unusual and this program had its normal share. There were two failures, however, which stand out above the others because of the magnitude of their impact on the program. Both of these failures resulted in destruction of the stator of the Starter/Generator such that the laminations had to be replaced and rewound. The rotor, in each case, survived with only superficial scars. The failures have indicated the need for careful application of protection circuits with regard to use of a permanent magnet generator but they have also provided dramatic evidence of the durability of the Samarium Cobalt solid rotor designed on this program.

Each of these failures has been documented extensively with a Failure Analysis report*. The following paragraphs in this report describe the circumstances, causes and corrective actions taken without the depth of supporting analysis.

5.2 GENERATOR FAULT - 15 October 1976

5.2.1 BACKGROUND

Phase I including rotor spin testing had been completed in December 1976 and Phase II and III go ahead had been issued 23 December 1975. Phase II (the generator and converter construction phase) was completed on 15 September 1976. In early October the generator was in unit tests prior to connection with the cycloconverter. Because the vibration level was high the generator had only been run up to about 16,000 RPM. The rotor was rebalanced and it was planned to proceed up to 21,000 RPM on the 15th unless the vibration was excessive.

5.2.2 FAULT DESCRIPTION

On 15 October 1976 the generator was being operated without being connected to the converter and with no electrical load applied. The vibration, operating temperature and no load voltage were being monitored closely as the speed was increased in steps. Vibration and voltage readings recorded before the fault are given below. Just after reaching 19,500 RPM a generator fault occurred with an explosion and flame shooting out of the generator at the anti-drive end of the machine. The generator drive was shut down within a few seconds after the fault occurred. The generator was then removed from the drive.

---

* GE Project Memorandums 76-404-065 and 76-404-065A documented Failure Analysis of 15 October 1976 generator fault. GE Project Memorandum 77-404-119 documented Failure Analysis of 28 October 1977 system fault.

Speed RPM	Line to Neutral Volts RMS	Vibration 's
12,000	185.2	Nil
18,000	275.8	2.0
-	286.2	4.4
19,500	294.4	6.8

5.2.3 INSPECTION AND OBSERVATIONS

The magnesium frame had burned away cavities in the vicinity of connectors J1 and J6. All the phase leads at J1 and J6 had been burned away (see Figures 68 and 69). The stator core had cavities where the lamination material had blown out and there were copper and steel deposits on the stator I.D. (see Figure 70). The rotor surface had some surface scuffing and smeared copper deposits (see Figures 71 and 72). There were white metallic particles throughout the machine wherever the cooling oil had circulated - especially dense in the oil sump area (see Figure 73). These particles were analyzed and found to be magnesium turnings.

5.2.4 CAUSE OF FAILURE

The generator fault was caused by metal turnings (chips of magnesium) which formed a partial bridge between exposed lead strands on the back of two power connectors J1 and J6. The chips had been introduced into the generator oil system by machining which was accomplished after the stator had been completed and the starter/generator assembled. Although this machining was at the lower side of the machine, the chips were circulated by the cooling oil flow. Connectors J1 and J6 were the two lower power connectors and metal chips were found at this level. When the generator speed was increased to 19,500 RPM the generated voltage between connector pins increased to a level where an arc over occurred. A high short circuit current was sustained for several seconds until the rotation of the permanent magnet rotor was essentially stopped. The high current induced high voltage in other stator winding which caused shorting at the other contaminated power connector. The high power (all the kinetic energy of the rotor) was dissipated in a few seconds melted the shorted stator windings and blew out stator teeth in the stack.

5.2.5 CORRECTIVE ACTION

The most obvious problem was the presence of metal chips within the machine. These were blamed on the machining which was done after completion of the stator and assembly of the starter/generator. It is recognized that some chips could have been present even without the late machine work if parts and assemblies were not thoroughly cleaned during assembly.

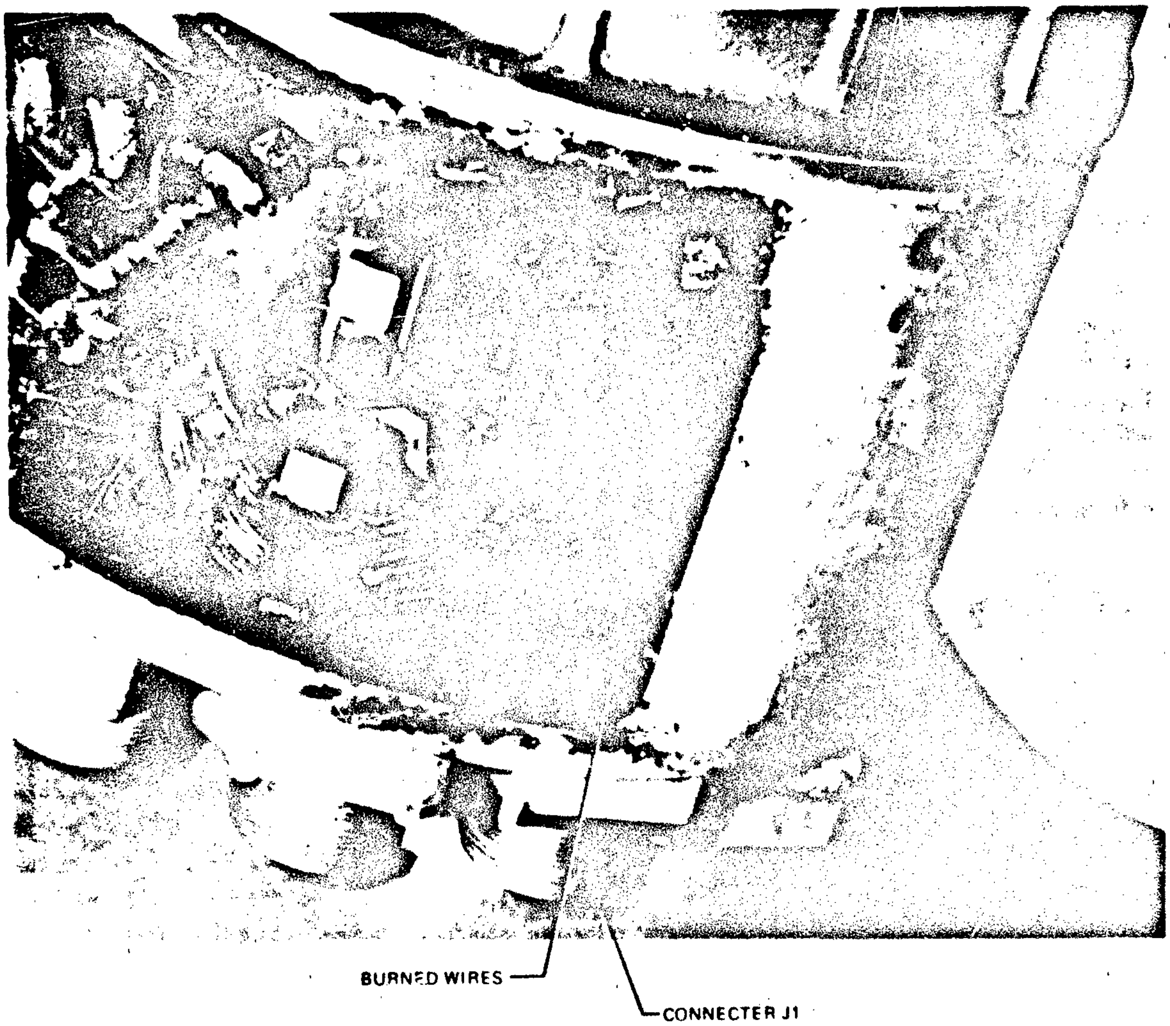


Figure 68. Burned Wires at J1

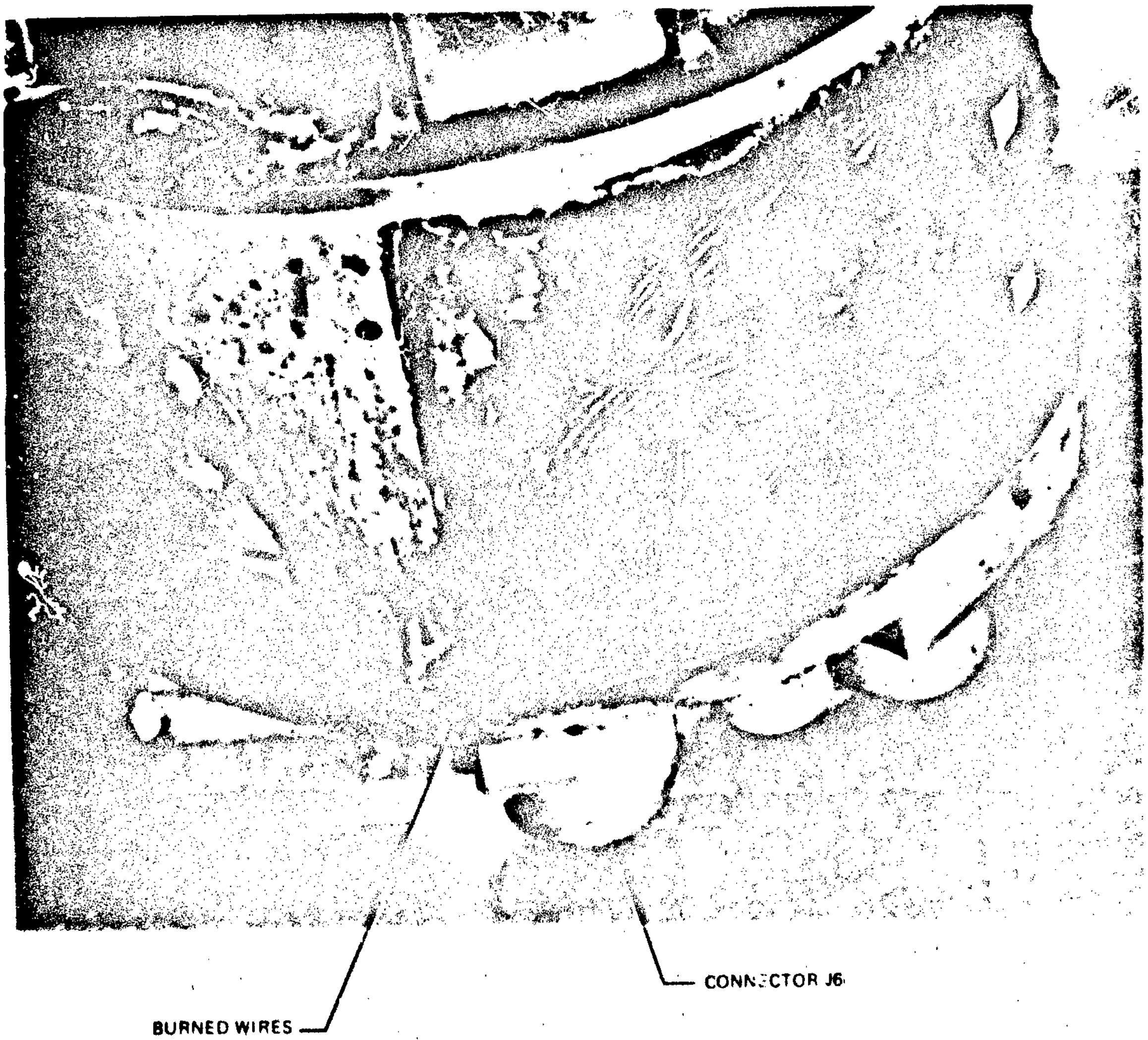


Figure 69. Burned Wires and Casting at J6

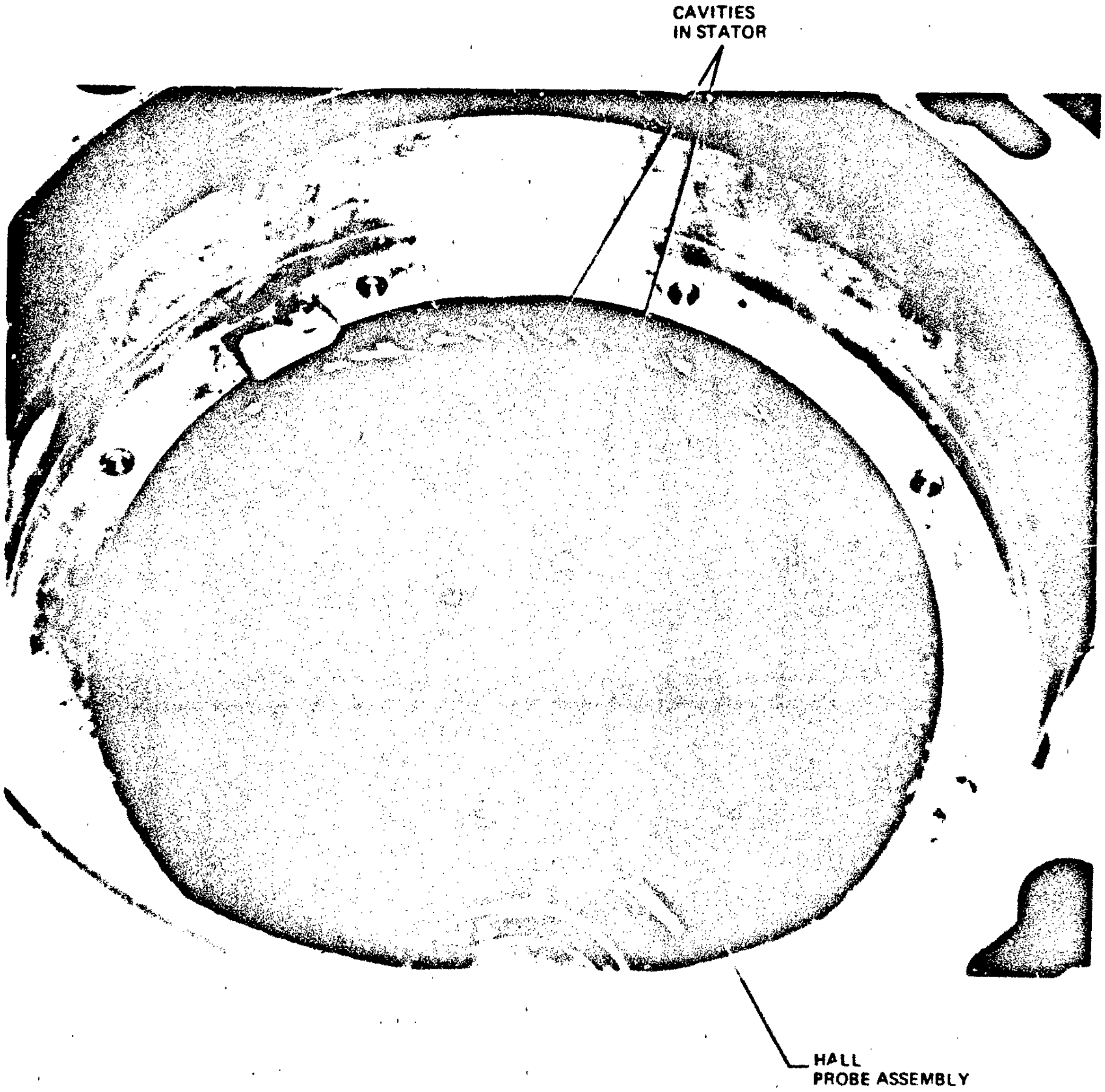


Figure 70. Stator Core

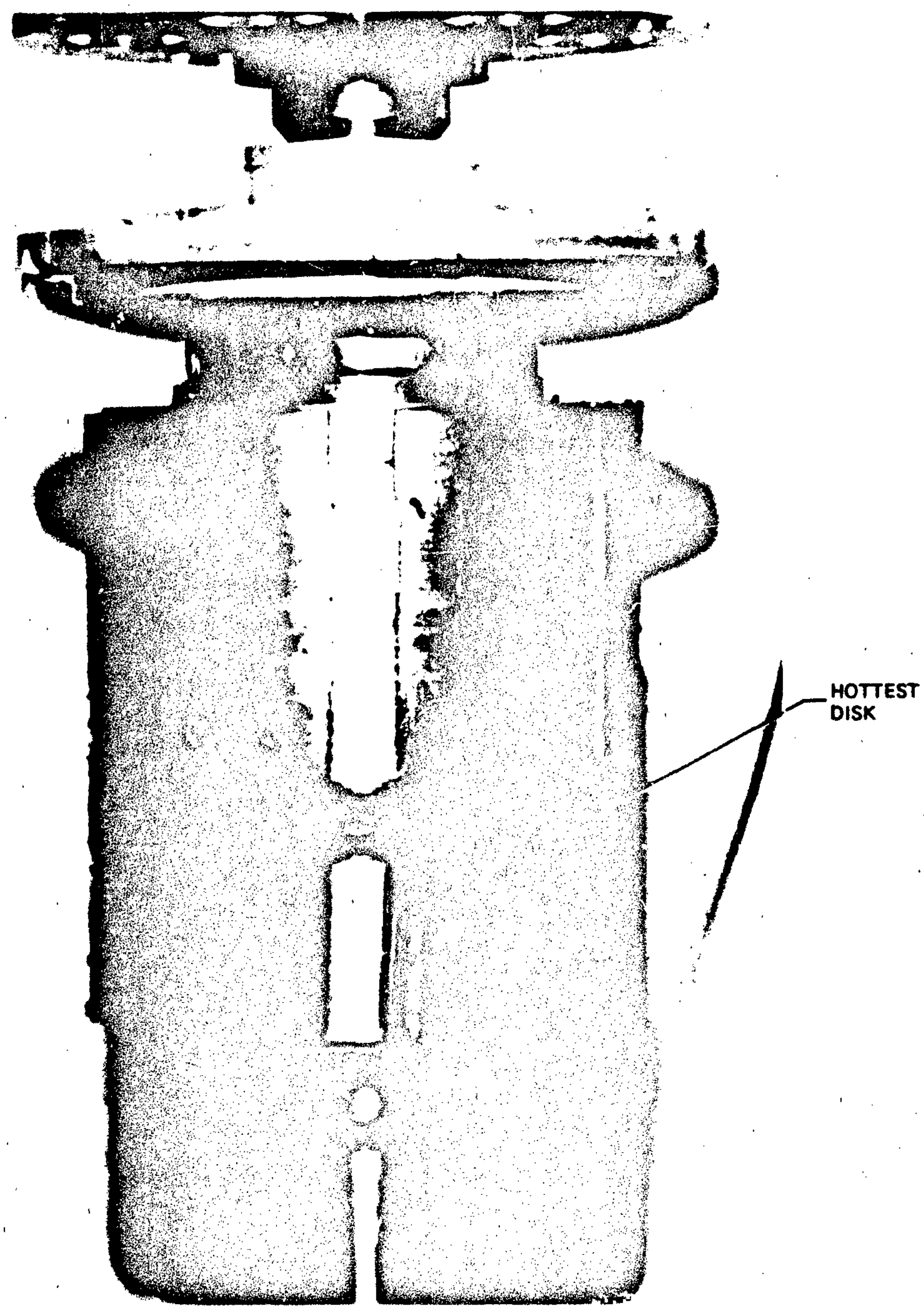


Figure 71. Rotor as Removed

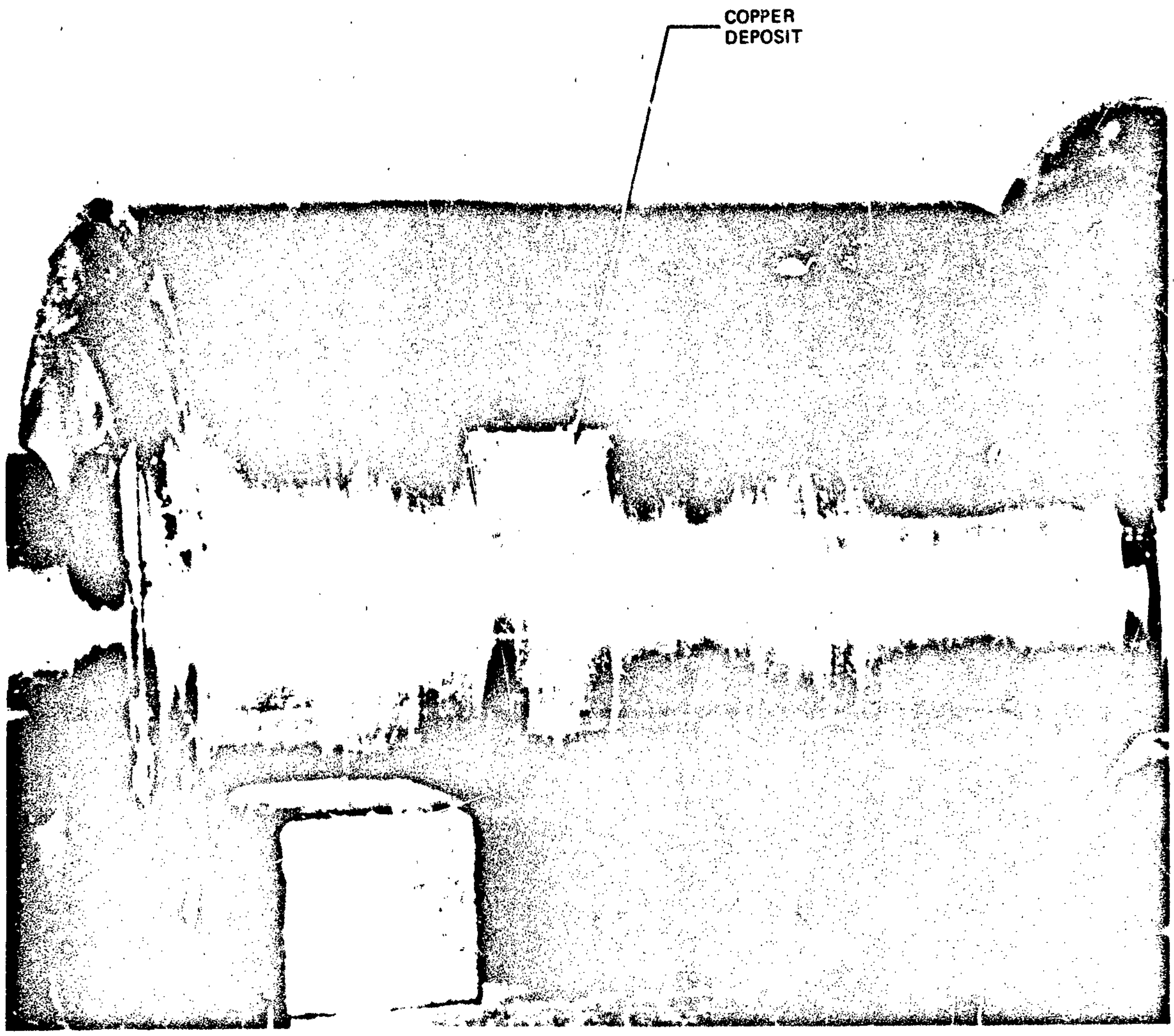


Figure 72. Rotor-Surface Wiped

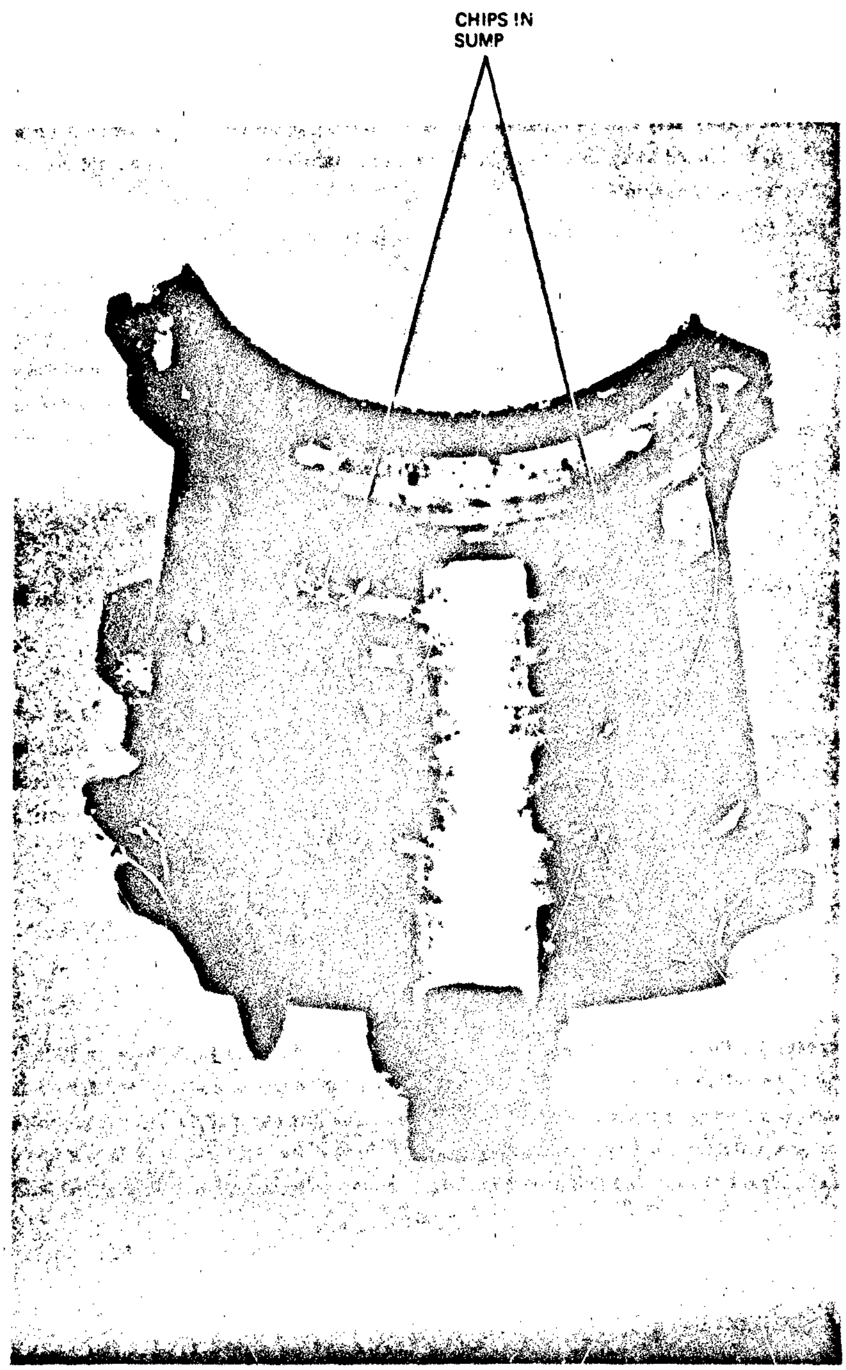


Figure 73. Sump Area of Frame

Corrective Action 1

Design machine so each assembly can be cleaned thoroughly during build up. This means eliminate pockets where chips might not be rinsed away thoroughly and design for fabrication which does not require machining into cavities in later steps of assembly.

In brief, design, plan fabrication and monitor manufacturing to get a clean chip free machine.

Corrective Action 2

The second corrective action item was to eliminate exposed lead strands at the back of the connector. These were not potted or in an environmental connector gasket because these materials were known to contaminate the cooling oil with silicone which promotes foaming. There was no connector available which sealed the leads in a non silicone material and was suitable for the voltage and current handling requirement. Instead of developing a suitable connector it was determined that a terminal block would be used for the power lead connection.

In brief, eliminate the internal exposed leads by bringing phase connection leads outside of the machine to a terminal block.

To accomplish these corrective actions it was determined that the stator and frame should be designed specifically for this machine instead of using an existing casting which did not provide adequate space or design freedom. The subsequent generator therefore was designed from the beginning with plans to machine the stator, frame and internal supporting structure out of solid stock rather than use existing castings which did not match the design criteria.

5.3 SYSTEM FAULT-28 October 1977

5.3.1 BACKGROUND

The generator except for the rotor had been redesigned and rebuilt after the 15 September 1976 fault. The rotor surface had been polished, tested and inspected and installed in the new stator and frame assembly. The generator had completed no load tests in Erie in September. The system testing was progressing well. Completed generate mode tests included operation at full load at three different input speeds and two power factors. Transient tests at several speeds and two power factors had also been taken for full load and load and a half transients.

5.3.2 SYSTEM FAULT DESCRIPTION

On 28 October 1978 Generate mode steady state tests at load and a half (225KVA) were being run. Tests had been completed @ 12,000, 15,000 and 18,000 RPM with .75 power factor load and at 12,000, and 15,000 with .95 power factor load. Within 15 seconds after application of the 225KVA, .95 Power factor load at 18,000 RPM, the system noise changed dramatically and a quick look by the test people revealed smoke coming from the generator. The converter off switch was hit immediately and drive stand stop button hit a second or two later. Thermal printout data was recorded within one minute of the fault while the drive stand was still

coasting to a stop. The time printout on this data was 11:40 AM. When the drive stand came to a halt the Hall Probe access cover on the generator was removed and it was noted that rotation of the drive stand by hand did not rotate the rotor of the generator. Another observation was that the generator oil flow meter contained blackened oil and black oil had sprayed out of the antidrive end of the generator. The photo in Figure 74. shows the generator on the drive stand with the blackened oil on the generator and adjacent floor area.

5.3.3 INSPECTION AND OBSERVATIONS

5.3.3.1 Thermal Test Data

Thermal data recorded during 225 KVA load runs immediately prior to the fault showed the generator was running cool. Thermocouples in the air gap read from 100 to 113°C and generator cooling oil had only a few °C rise inlet to outlet. In the converter, however, the SCR case temperature had climbed to 147.1°C in the run prior to the failure. In the data taken within one minute after the fault generator air gap thermocouples range up to 184.1°C and the generator outlet oil temperature measured 173.6°C. The converter SCR case temperature read 136°C.

5.3.3.2 Test Set Up

A continuity check revealed one contactor in the generator output to converter power tables was welded closed. This contactor opened during inspection. Figure 75 is a photo of the burned contacts.

Another check revealed the circuit breaker in the pump motor of the converter cooling oil cart had tripped open. This would shut off the cooling oil flow to the converter which was the cause for the high SCR case temperature noted above.

5.3.3.3 Cyclo Converter

There was no damage apparent in the converter from a visual inspection. From measurements, however, 4 SCRs were found shorted. Figure 76 shows one of the SCRs that was sectioned for further analysis. This shows the burned surface area of the cathode plate and silicon chip which is evidence of damage from excessive current and temperature.

There was no other damage in the cycloconverter. Leakage measurements were taken on all the other SCRs (50 unshorted ones) and all were within limits.

5.3.3.4 Starter Generator

The stator of the machine was destroyed by the fault currents. The rotor and stator in fact looked very much like they did after the 15 October 1976 fault. These are shown in Figures 77 and 78. This time, however, the metal pieces in the oil were copper and no evidence of aluminum structure machinings were present. No structural members were damaged.

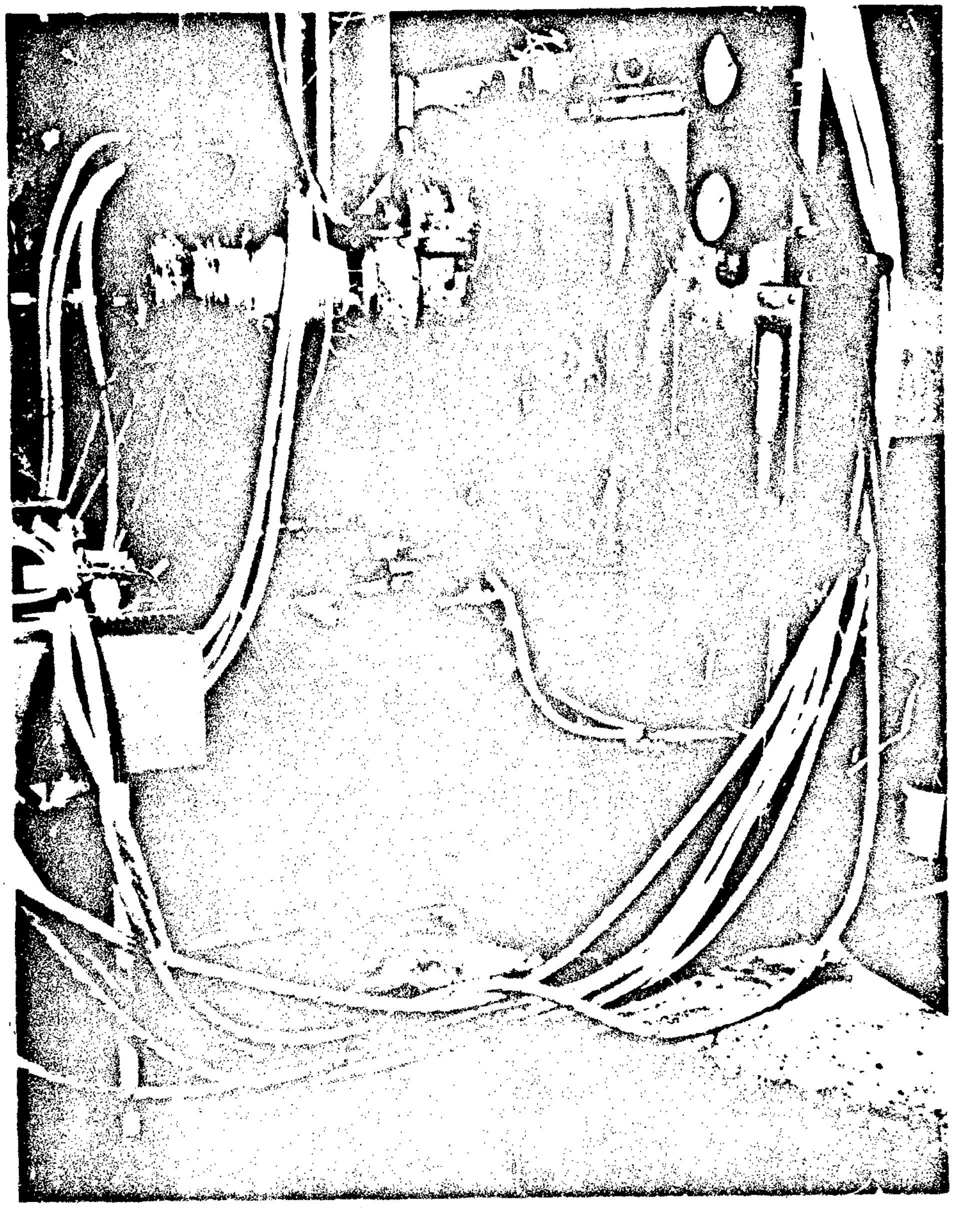


Figure 74. Generator on Drivestand

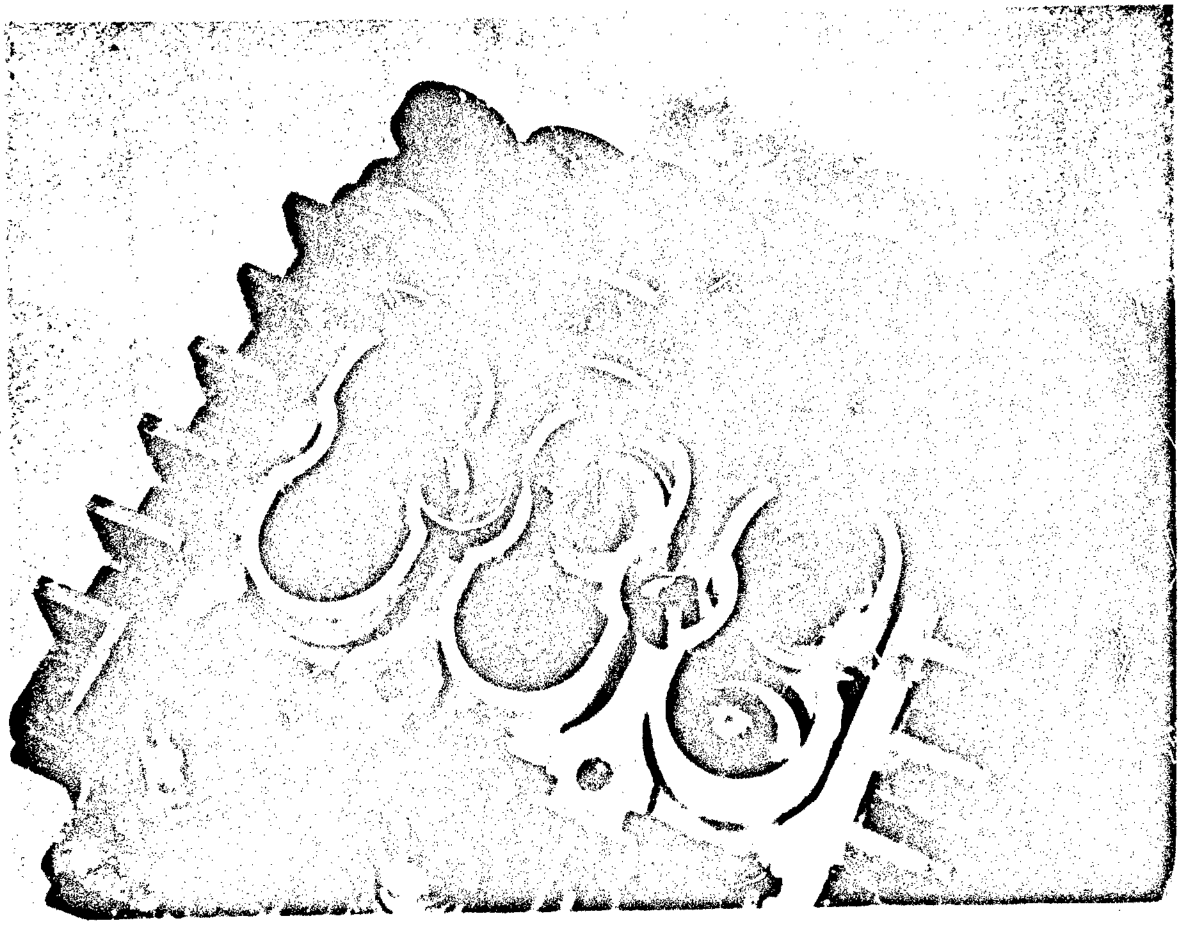


Figure 75. Contactor

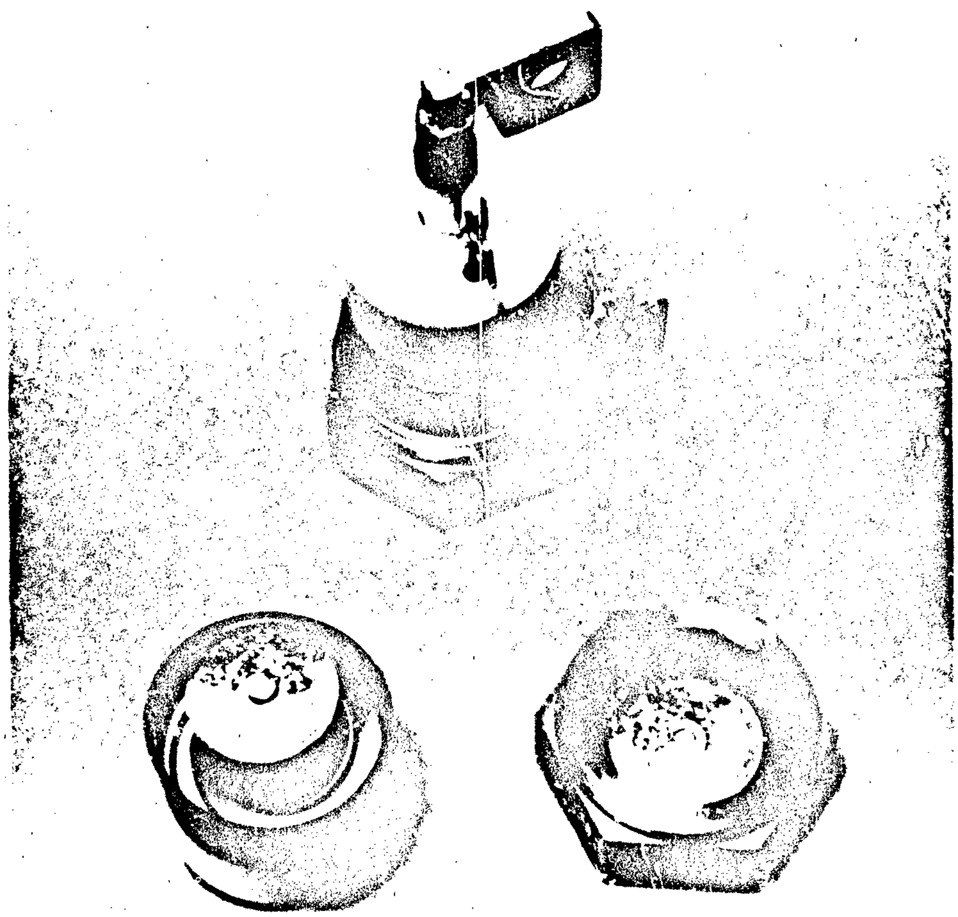


Figure 76. Shorted SCR Sectioned

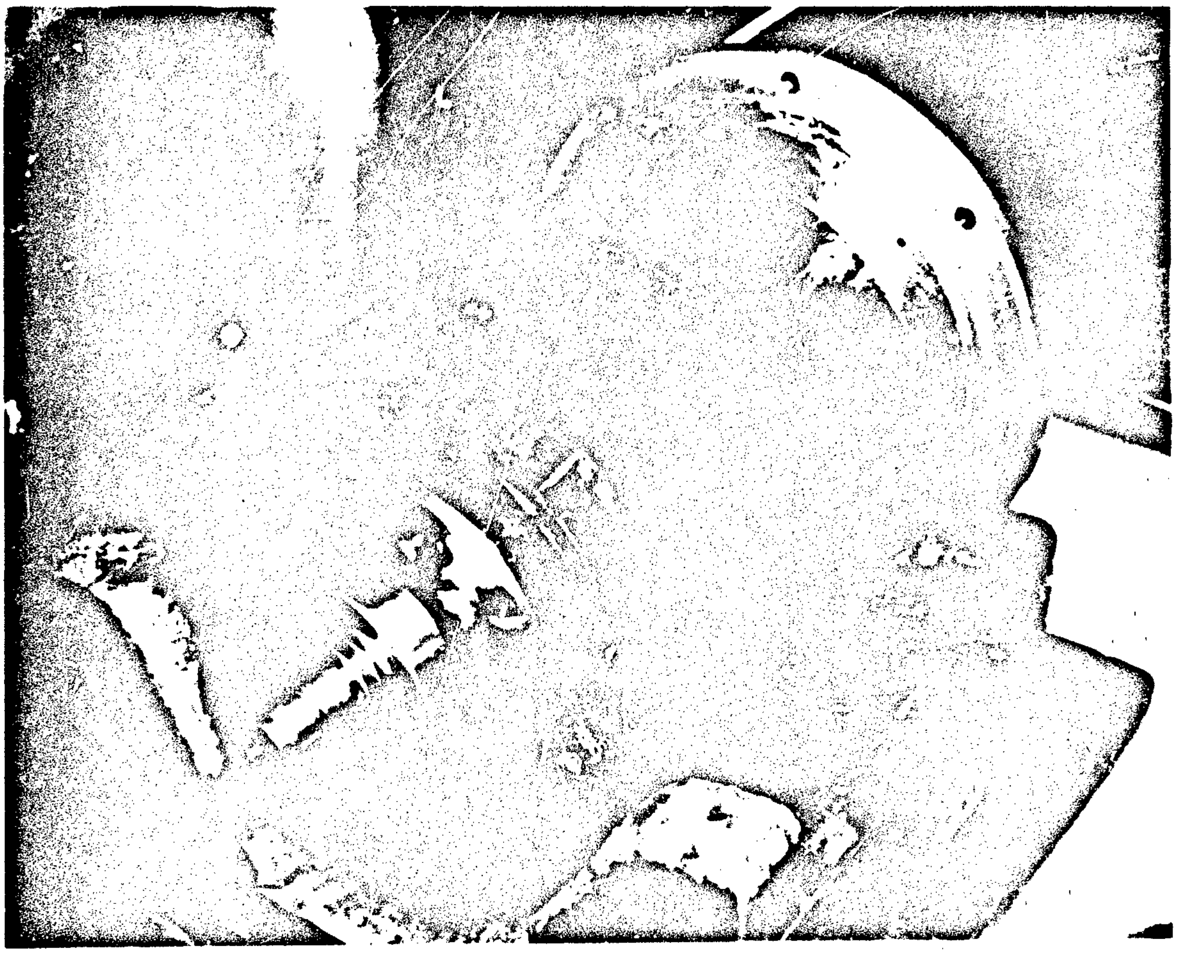


Figure 77. Rotor as Removed

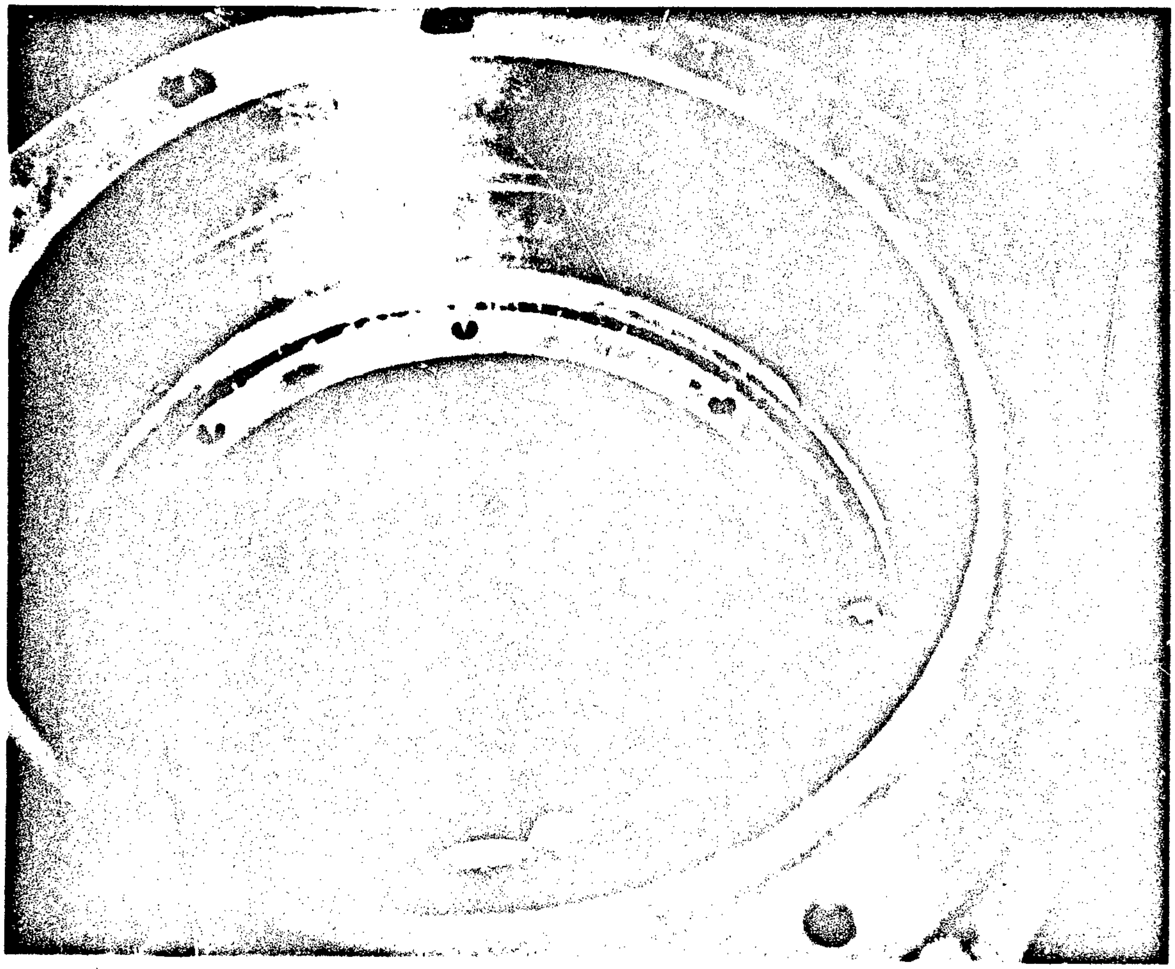


Figure 78. Burned Stator

No other catastrophic damage occurred in the generator but the bearings, oil pump, current transformers and stator cooling shroud were replaced along with a new stator wound when the generator was reassembled.

The mechanical disconnect operated during the fault as was evident when the drive stand was rotated by hand without a corresponding rotation of the rotor. The disconnect operation was attributed to the high pulsating torque resulting from the fault which was converted to axial vibration in the disconnect by the sloped faces of the curvic coupling.

5.3.4 CAUSE OF FAILURE

There were six findings resulting from the test observations, review of test data, inspection of the test equipment and examination of the converter and generator, that were significant to the analysis of the 150 KVA starter-generator-converter electrical system failure. These findings were as follows:

1. The increase in converter SCR case temperature, reaching 147.1°C prior to the system fault. This temperature is considered substantially in excess of the 125°C SCR junction temperature rating and critical to performance of the device.
2. The electrical motor used for pumping converter cooling oil from the external oil cart facility was found disconnected from the power line due to a thermal switch trip. The trip cause was attributed to use of an oil pump facility of insufficient capacity.
3. The three contacts of the line circuit interrupter contactor, connected in phases T2, T5 and T8 between the generator and converter, were found closed. The closure was attributed to use of the voltage suppression diode. All other contacts were open.
4. Four converter SCR's connected to the same phases as the contactor with closed contacts, were found shorted. The remaining SCR's were not damaged.
5. Insulation on three of the nine generator phase windings was burned from high temperature exposure. These phase windings appeared to be the same phases connected to the faulted contacts and SCR's.
6. The generator coil/phase windings were uniformly heated as would be expected from a sustained short circuit fault.

After review of the test data and fault occurrence, and an examination of the test facilities and equipment tested, the failure sequence was reconstructed and determined to be as follows:

a. The electric motor used for pumping oil to cool the converter was tripped from the line by the motor protective thermal switch.

b. Temperature of converter components increased due to lack of circulating coolant, exceeding the temperature limit for acceptable performance of the SCR's.

c. A converter miscommutation occurred causing a short circuit across an SCR. The SCR did not recover resulting in short circuit failure of the remaining three SCR's connected in the same phases.

d. The contactor connected in the same phases partially opened, but sustained arcing developed causing the contacts to remain closed.

e. The closed contacts placed a direct short circuit across three generator phase windings. The generator delivered power to this short circuit until shut-down (approximately 33 seconds) which was more than sufficient time to destroy the generator stator.

f. The generator disconnect device disconnected the generator from the drive sometime during the fault occurrence.

The conclusions reached from the failure occurrence, examination of equipment tested, inspection of test facilities, and the analysis presented, are as follows:

1. The failure was caused by loss of converter oil cooling, due to a power disconnect of the oil pump motor, resulting in excessive temperatures and subsequent failure of four SCR's.

   Protective circuitry in the converter functioned to open circuit interrupter contacts in the generator and load lines except for the contacts in phase windings connected to the failed SCR's. The contacts in these phases arced and remained closed permitting application of a three-phase short circuit load to the generator that remained sufficiently long during generator rotation to destroy the stator. Contact arcing was attributed to use of a voltage suppression diode connected across the contactor coil.

2. Generator and system performance tests conducted during the several weeks prior to the fault occurrence had demonstrated excellent performance of the generator and the generator-converter electrical system. The fault is not attributable to the electrical system constructed under this contract.

3. The generator rotor withstood the affects of the severe electrical stator fault. The mechanical and magnetic condition was acceptable for reuse of the rotor.

   Except for the generator main stator core and windings, and the faulted converter SCR's, all other components of the electrical system appear acceptable for reuse. The generator bearings should be replaced.

5.3.5 CORRECTIVE ACTION

Much of the corrective action taken to avoid any recurrence of this type of fault involves adding protection interlock to the system test set up. Figure 79 is a block diagram of the System Test Set Up with protection interlocks. Main power flow is through the center of the diagram starting at the drive stand and proceeding through the generator, generator contacts, converter and load contactors to the load. Interlocks added to this test set up as corrective action from the fault occurrence are indicated by numbers which correspond to the descriptions below. The interlock paths which are not numbered were in the set up when the fault occurred and of course were retained in subsequent system tests with the new added protection.

1. Interlocks monitoring converter cooling oil temperature and pressure were added to the converter cooling oil cart. These interlocks feed into the converter protection circuit loop and through it will turn off the converter and open the load contacts.

2. The generator oil cooler previously had low pressure and high temperature trips which would shut down the drive stand. These switches were tied in with the converter protection circuits to provide additional protection by operating the mechanical disconnect, both contactors and turning off the converter.

3. Thermocouples imbedded in the stator had previously been used to monitor air gap temperature. One of these has since been used to provide interlock protection in addition to the monitoring function. It will

   a. shut down the drive stand

   b. operate the mechanical disconnect

   c. operate the generator power line contactors

   d. turn off the converter

   e. operate the load contactor.

4. A thermal switch was added to the hot end of the SCR cold plate in the converter. This switch will turn off the converter and operate the load contactors through the converter protective circuits.

Other Changes

In addition to the above the arc suppression diode used across the coil of the contactors was removed. Tests run on the contactor showed a decrease in dropout time of this contactor from 225 milliseconds to 24 milliseconds.

A shear section was also added to the stub shaft within the generator. This provides a means of removing drive power from the generator if something were to jam up in it (like from a bearing failure). The shear section would not shear for momentary torque loads within system ratings.

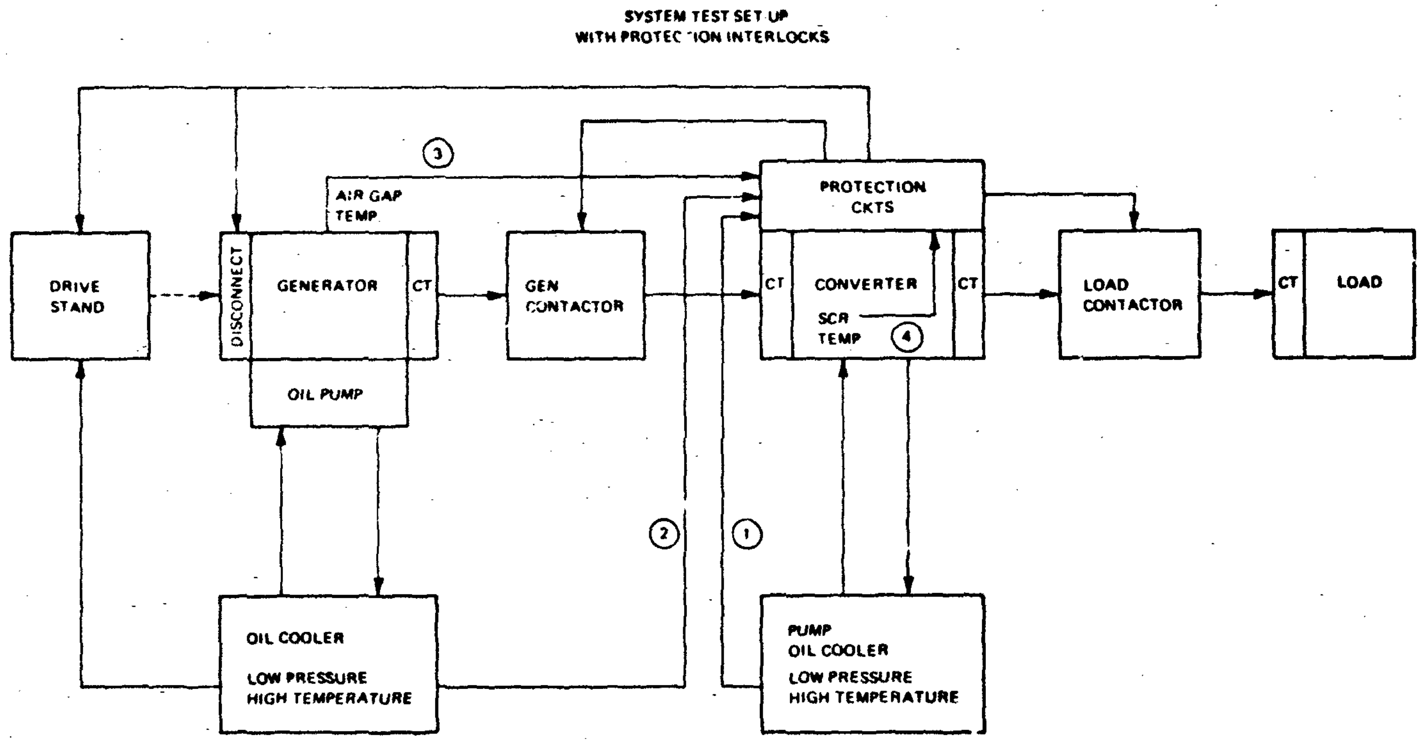


Figure 79. System Test Set Up with Protection Interlocks

SECTION VI

FINAL TEST RESULTS

6.1 GENERATOR TESTING

The test plan which describes the testing to be performed on the 150 KVA permanent magnet generator is contained in Appendix A of this report.

6.1.1 PHYSICAL INSPECTION

The generator was assembled and subjected to a dimensional and drawing audit as required by paragraph 3.2 of the Phase III Test Plan which is contained in Appendix A of this report. Contained in Appendix B of this report is a copy of inspection report. The discrepancies found did not affect performance and the generator was delivered to test.

6.1.2 GENERATOR TEST

The generator was subjected to the tests listed in paragraph 3.3 of the test plan contained in Appendix A of this report in most areas. Areas where the test plan was not followed were areas where operation limitations had been identified, thermal and vibration, and in areas where major concern about protection the generator during performance of this test could not be assured. The following paragraphs follow the test plan order.

6.1.2.1 Resistance and Inductance

The generator phase to neutral resistance was measured using a portable electronic bridge. The resistances as measured at 25°C are as follows:

- Stator

Phase to Neutral	Resistance In Ohms
1-N	0.0122
2-N	0.0120
3-N	0.0117
4-N	0.0123
5-N	0.0122
6-N	0.0120
7-N	0.0118
8-N	0.0117
9-N	0.0118

The average stator resistances value is .0120 ohms which is within 9% of the calculated value which is .011 ohms. The resistance balance is within 5%. Both values are acceptable.

- Current Transformers

Phase	Control Connector Pin Numbers	Resistance in ohms
1	23-15	42.37
2	24-15	42.40
3	21-15	42.55
4	16-15	42.38
5	17-15	42.30
6	18-15	42.39
7	19-15	44.39
8	20-15	46.36
9	22-15	44.01

- Disconnect Coil Resistance

Control Connector Pins 8-9 — 1.096 ohms

- Hall Probe Assembly

Control Connector Pins Number	Resistance in ohms
5-6	105
3-4	90
1-2	92
11-12	44
11-13	65
11-14	71

All the above listed resistance are within drawing limits.

The inductance of the stator winding were measured using a general radio automatic RLC bridge, Model Number 1683.

The individual phase inductance measurement results are shown below. The rotor was rotated in an attempt to record the highest and lowest values for each phase.

Lead Measured	High μh	Low μh
T_1-N	13.55	10.62
T_4-N	13.40	10.43
T_7-N	13.05	10.10
T_2-N	13.06	10.14
T_5-N	13.08	10.08
T_8-N	12.98	9.98
T_3-N	13.05	10.01
T_6-N	13.41	10.05
T_9-N	13.40	10.41

The phase to phase inductances where measured as follows:

Lead Measured	High μh	Low μh
T_1-T_4	26.74	22.83
T_1-T_7	26.49	22.64
T_4-T_7	26.35	22.42
T_3-T_6	26.55	22.70
T_6-T_9	26.64	22.72
T_3-T_9	26.46	22.53
T_2-T_5	26.10	22.17
T_2-T_8	26.17	22.32
T_5-T_8	26.06	22.18

The calculated value of the commutating inductance was 13μ henries or 26μ henries phase to phase. The measured values shown above are well within expected results.

6.1.2.2 Dielectric Strength (Hi-Pot)

The electrical circuits in the generator were each subjected to a Hi-Pot test with a General Electric Hi-Pot Tester. The Hi-Pot probe was applied to the circuit and the ground clamp was attached to the generator frame. The applied voltage level and time duration used for the different circuits are shown below.

Generator Circuit	Test Condition		Condition
	Voltage V_{RMS}	Application Time	
Stator Windings*	1600	1 Min	OK
R1-Ground	1600	1 Min	OK
R2-Ground	1600	1 Min	OK
R3-Ground	1600	1 Min	OK
R1-R2	1600	1 Min	OK
R2-R3	1600	1 Min	OK
Current Transformer	1600	1 Min	OK
CT to Ground	1600	1 Min	OK
CT to Stator Winding	1600	1 Min	OK
Thermo Couples	1600	1 Sec	OK
Disconnect Coil	600	1 Min	OK

*Test made with grounding strap connecting the three neutral leads removed. Each neutral connector to 3 phases 120 electical degrees apart.

6.1.2.3 **Disconnect Operation Check**

A 28 Volt DC Power Supply was connected to the disconnect coil thru the control connector. Momentary power was applied and the disconnect operated. The out board clutch plate rotated freely when turned by the generator input stub shaft without the rotor turning. The disconnect was reset by removing the "Faspin" and pulling the reset T-bar.

The above was repeated three times with the disconnect functioning properly each time.

6.1.2.4 **Generator Set-up and Spin Check**

Shown in Figure 6.1-1 is the generator mounted on the 200 Horsepower Drive Stand which shows the following performance monitors:

- Vibration Monitors
  - Drive End
  - Anti-Drive End
- Oil Temperature
  - Oil In
  - Oil Out

The following parameters where also instrumented in this set up.

- Oil Flow
- Oil Pressure into Generator
- Oil Pressure out of Generator
- Speed
- Generated Volts
  Instead of nine voltmeters, one voltmeter was connected to a 9 position transfer switch which was connected to each generator output phase.
- Air Gap Thermocouple
- Brake Circuit Voltage

The results of the operation checkout is shown in Figure 80. The speed was increased in steps of 4,000 RPMS instead of the test plan of 2,000 RPM steps.

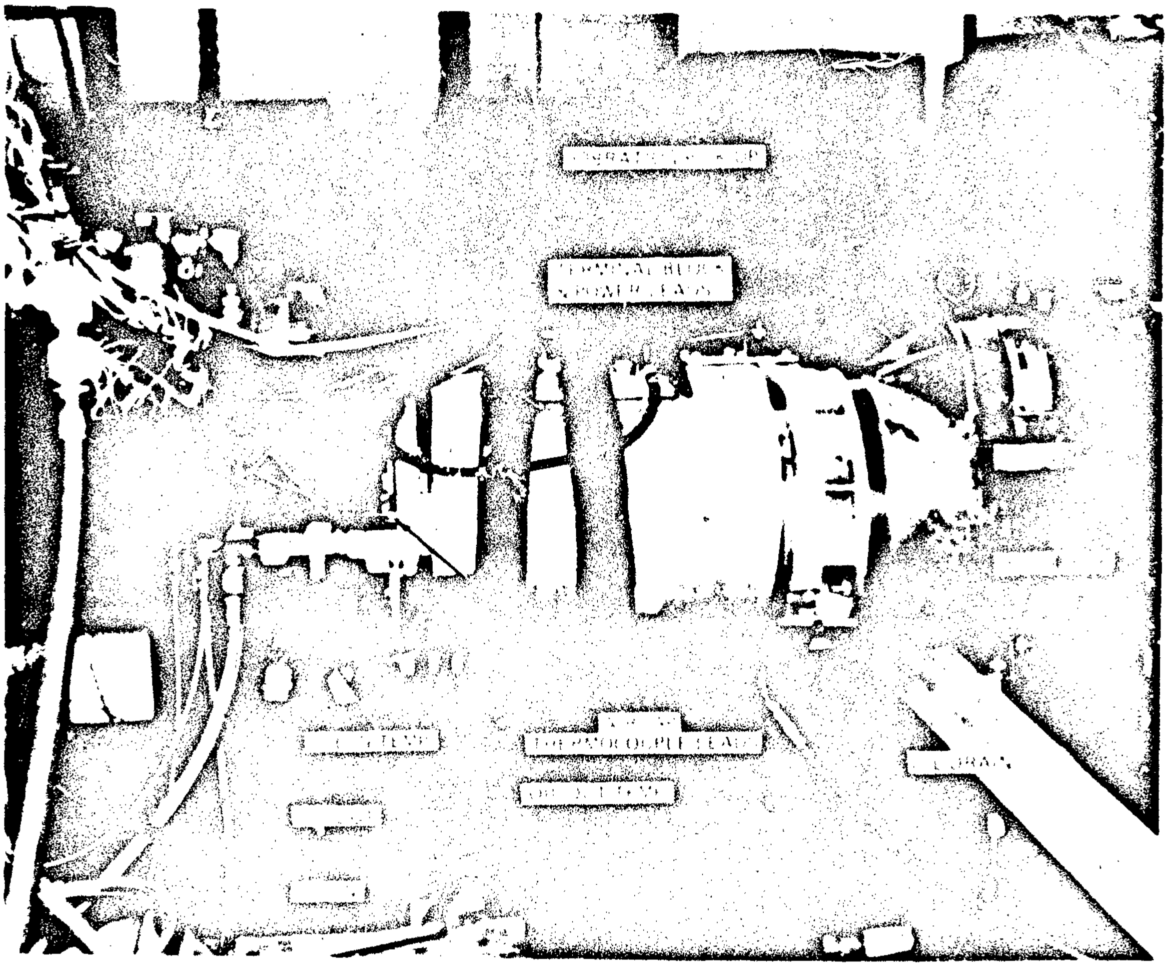


Figure 80. Generator Test Set Up

	Oil						Vibration							
	Pressure		Temperature		Flow		G's RMS 10 KHZ Filter		Stator Airgap Thermocouples					Phase Voltage
Generator Speed	In PSIG	Out PSIG	In °C	Out °C	Meter	GPM	D. F.	A. D. E.	0	90	180	270	Condition	L-N
4000	10	18	27	29	41	1.4	–	.4	32	32	32	32		61.9
8000	10	18	40	44	55	1.6	–	.6	55	55	55	54		123.0
12000	14	24	59	64	100	3.4	–	.7	88	89	89	89		182.3
12000	12	22	61	72	105	3.6	–	.8	107	109	105	106	Stablized	177.9
16000	14	24	90	103	135	–	–	1.3	152	154	151	152	Stablized	206.8
18000	16	26	60	78	130	4.5	–	1.5	139	142	139	141	Stablized	262.2

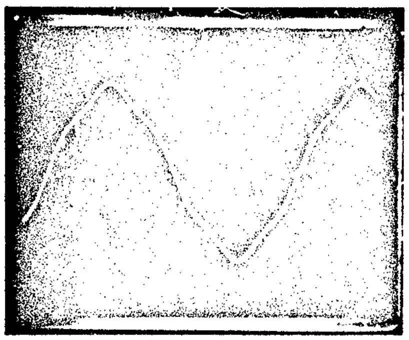
At the conclusion of 18000 RPM recording the disconnect was operated and it operated properly.

A picture of the generator no-load voltage wave shape is shown in Figure 81 for phase to neutral and for phase to phase condition at a speed of 11,914 RPM or a generated frequency of 1390 Hz. The generator voltage for different phases at the same speed where balance to within 0.1 volts.

Items 6 thru 10 of the test plan where not conducted due to delays experienced in solving the vibration/balance problem after the second generator failure. The results of these tests where not considered critical to performance check of the generator prior to the generator operating with the cycloconverter and were therefore bypassed.

After completing the above generator tests, the generator was disassembled and visually inspected. The only noticeable change was the rotor surface had discolored to a similar color as had been noted previously. The balance of the rotor was checked with the bearings still assembled on the rotor and was found to be still within limits. The generator was reassembled, hi-potted as before, and subjected to a brief spin check before it was delivered to system testing with the converter.

PHASE VOLTAGE
100 VOLTS/CM
.1MSEC/CM



LINE TO LINE VOLTAGE
200 VOLTS/CM
.1MSEC/CM

Figure 81. No-Load Generator Voltage at 11914 RPM, 1390 Hz

6.2 SYSTEM TESTING

6.2.1 GENERATE MODE

Generate mode performance tests were run with the machine mounted on a 300 HP drive stand. The high frequency transmission lines were approximately 35 feet long and the 400 Hz feeders to the point of regulation were about 20 feet long. Linear loads with parallel resistance and inductance were used.

Tables 3, 4, and 5 list the steady state performance data. Note that the data in Table 5 of operation at 18,000 RPM was taken about 4 months before that on the other sheets. Machine speed was limited to 15,000 RPM after the second machine rebuild to limit the rotor temperature as explained in paragraph 4.2.1.3.3. The converter configuration was slightly different when the 18,000 RPM data was taken and this data is included only to show there are no basic performance problems at increased speed. The principle difference in the converter was reduction of feedback gain of the path labled G3 in Figure 23 after the 18,000 RPM data was taken.

Figures 83 through 88 show the output transient response of the system with application and removal of 150 KVA Loads at .75 and .95 power factor and for 12,000, 15,000 and 18,000 RPM. Figures 89 through 93 show the output transient response for 225 KVA transients at .75 and .95 power factors and for 12,000 and 15,000 and for .75 power factor at 18,000 RPM. Figures 94 through 97 show the transient response for a 300 KVA load change at .75 and .95 power factor and for 12,000 and 15,000 RPM. The time to return to steady state after application of a 150 KVA load is measured to be 32 to 50 milliseconds on the recordings of Figures 83 through 88. The time to return to steady state after removal of rated load is measured on these same recordings to be 12.5 milliseconds or less.

It should be noted that the converter circuits are designed to slow the transient response upon application of the load as in a wound rotor application. In the wound rotor application, the output voltage response is slowed to provide time for the machine voltage to recover. The permanent magnet machine does not have this long time constant since the generator is at full excitation all the time. The response to load application could be as fast as the response to load removal for the PMG application. In this program, however, where the PMG machine is to be operated in parallel with a wound rotor machine comparable time response to transients is desirable.

Table 6 lists the results of fault tests and Figures 98 through 105 show response of generator and system output voltage and current during the faults.

Table 7 lists the results of tests of the generate mode protective functions.

Finally, in Table 8 are the results of the generate mode efficiency tests. Input power was measured with a torque shaft between the drive stand and the machine. Note that the losses include all feeder losses as well as those of machine and converter.

Generate mode performance in general is excellent. Fault performance is slightly below spec with 2.5 to 3 PU currents obtained rather that full 3 PU as specified. This deficiency is caused by marginal stability of the current limit loop. It is believed that full specified fault currents could be achieved with additional work on the current limit circuit.

TABLE 3

ELECTRICAL SYSTEM TEST DATA SHEET

GENERAL ELECTRIC BINGHAMTON, NEW YORK

Title of Test GENERATE PERFORMANCE Specification ______ Para ______ Test No ______ Sheet No 1

Generator Model No. 2CM 404 A1 Serial No ______

Converter/Control Model No 3S 3480 OF 139A1 Serial No 7610001

TESTED BY ADD, OL

DATE 17 MAR 78

NOTE NO	RUN NO	GEN SPEED RPM	TOTAL LOAD KVA	TOTAL LOAD PF	VOLTAGE φA VOLTS	VOLTAGE φB VOLTS	VOLTAGE φC VOLTS	VOLTAGE φA-B VOLTS	VOLTAGE φB-C VOLTS	VOLTAGE φC-A VOLTS	CURRENT φA AMPS	CURRENT φB AMPS	CURRENT φC AMPS
	1433	12000	0		115.1	115.[illegible]	116.0	198.8	200.0	199.[illegible]	0	0	0
			37.5	.75	114.7	114.9	114.5	198.5	199.[illegible]	[illegible]	[illegible]	[illegible]	104
			75		114.3	119.5	119.[illegible]	197.5	197.6	196.6	2.8	211	211
			112.5		115.0	115.0	115.0	197.[illegible]	200.3	199.5	3.8	317	[illegible]
			150		115.3	115.3	116.[illegible]	197.8	200.2	[illegible]	430	424	425
			225		114.2	119.8	116.[illegible]	198.[illegible]	199.[illegible]	198.0	645	640	651
			300	↓	118.1	117.8	117.8	153	190.3	198.8	817	811	817
			37.5	.95	118.3	118.4	[illegible]	197.3	197.2	198.5	[illegible]	19	[illegible]
			75		114.9	[illegible]	[illegible]	198.5	200.[illegible]	199.5	223	217	223
			112.5		[illegible]	[illegible]	[illegible]	200.4	199.5	199.3	333	333	331
			150		115.3	115.4	115.3	200.5	200.0	199.6	442	436	437
			225		116.5	116.5	116.5	201.0	201.7	202.3	629	644	617
	↓	↓	300	↓	113.5	117.9	117.6	199.5	199.5	199.5	831	804	812

TOTAL LOAD KVA	WATTS/PHASE φA KW	WATTS/PHASE φB KW	WATTS/PHASE φC KW	HARMONIC CONTENT % φA	HARMONIC CONTENT % φB	HARMONIC CONTENT % φC	VOLTAGE MODULATION (V) φA	VOLTAGE MODULATION (V) φB	VOLTAGE MODULATION (V) φC	DC CONTENT MV φA	DC CONTENT MV φB	DC CONTENT MV φC	FREQ HZ	CONTACTOR VDC	GENERATED	GENERATED	TRANSIENT	TRANSIENT	TRANSIENT V/G
0	0	0	0	2.8	2.8	2.7	.43	.40	[illegible]	[illegible]	0	10	400.1		[illegible]	62			.7
37.5	1.3	1.3	1.4	1.5	1.5	1.5	.37	.48	.43	30	2	5			167	53			.7
75	18.[illegible]	18.2	19.2	1.8	1.1	1.2	.44	.33	.50	2	-10	20			165	65			.7
112.5	28.[illegible]	25.[illegible]	28.[illegible]	.8	1.7	1.7	[illegible]	[illegible]	.55	0	-13	22			140	91			.7
150	38.[illegible]	37.[illegible]	38.[illegible]	2.9	2.8	2.7	.41	.35	.55	3	-2	7			135	141			.7
225	55.3	56.0	56.2	2.9	2.8	2.7	2	2	.8	40	60	.8			150	192			.75
300	70	70	70	1.2	1.5	1.3				[illegible]	72	140			139	237			.9
37.5	12.[illegible]	11.8	12	2.2	2	2	.37	.31	.33	1.8	10	22			[illegible]	67			.7
75	24.3	24.[illegible]	24.1	[illegible]	[illegible]	[illegible]	.33	.32	.46	-5	[illegible]	0			160	81			.7
112.5	36.1	36.5	36.3	1.2	[illegible]	[illegible]	.39	.31	.1	0	5	.2			155	113			.7
150	49.3	48.6	41.2	2.4	2.2	2.2	.59	.59	.37	.5	5	20			151	197			.7
225	73	74	73	[illegible]	[illegible]	2.0	1.1	1.1	1.0	10	5	10			142	215			.75
300	94	97	91	.6	.6	.6							↓		131	285			.75

NOTES ______

TABLE 4

ELECTRICAL SYSTEM TEST DATA SHEET

GENERAL ELECTRIC BINGHAMTON, NEW YORK

Title of Test ______ Specification ______ Para ______ Test No ______ Sheet No 2

Generator Model No ______ Serial No ______

Converter/Control Model No ______ Serial No ______

TESTED BY [illegible]

DATE [illegible]

Note No	Run No	Gen Speed RPM	Total Load KVA	Total Load PF	Voltage φA Volts	Voltage φB Volts	Voltage φC Volts	Voltage φA-B Volts	Voltage φB-C Volts	Voltage φC-A Volts	Current φA Amps	Current φB Amps	Current φC Amps	Watts/Phase φA Watts	Watts/Phase φB Watts	Watts/Phase φC Watts
	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]						
			75		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]						
			112.5		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]						
			150		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]						
			225		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]						
			[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]						
			37.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]						
			75		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]						
			112.5		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]						
			150		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]						
			225		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]						
	[illegible]	[illegible]	300	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]						

Total Load KVA	Harmonic Content (%) φA	Harmonic Content (%) φB	Harmonic Content (%) φC	Voltage Modulation (V) φA	Voltage Modulation (V) φB	Voltage Modulation (V) φC	DC Content MV φA	DC Content MV φB	DC Content MV φC	Freq Hz	Contactor VDC	Generator 16	Generator 15	Transient V.D
[illegible]	23	23	22	9	10	10	2	.5	.5	[illegible]		202	61	1.1
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2	5	5			209	[illegible]	1.0
75	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			200	[illegible]	[illegible]
112.5	22	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2	[illegible]	[illegible]			194	[illegible]	[illegible]
150	34	32	32	12	13	1	[illegible]	[illegible]	[illegible]			[illegible]	115	[illegible]
225	[illegible]	[illegible]	[illegible]	2	1	2	20	[illegible]	40			181	[illegible]	1.0
[illegible]	[illegible]	[illegible]	[illegible]				40	25	72			[illegible]	285	
37.5	[illegible]	[illegible]	[illegible]	12	10	4	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	1.0
75	[illegible]	[illegible]	11	[illegible]	[illegible]	19	[illegible]	5	[illegible]			195	81	[illegible]
112.5	21	[illegible]	23	[illegible]	13	12	2	2	-			[illegible]	111	[illegible]
150	31	21	21	12	15	[illegible]	[illegible]	9	10			[illegible]	97	[illegible]
225	[illegible]	[illegible]	[illegible]	1	[illegible]	2	5	5	12			[illegible]	[illegible]	[illegible]
300	[illegible]	[illegible]	[illegible]				[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	290	

NOTES LOAD BANK SET SAME AS SHEET 1

TABLE 5

ELECTRICAL SYSTEM TEST DATA SHEET

GENERAL ELECTRIC BINGHAMTON, NEW YORK

Title of Test ______ Specification ______ Para ______ Test No ______ Sheet No 3

Generator Model No ______ Serial No ______

Converter/Control Model No ______ Serial No ______

TESTED BY ABQ, DL, AW
DATE 27 OCT 77

NOTE NO	RDG NO	GEN SPEED RPM	TOTAL LOAD KVA	TOTAL LOAD PF	VOLTAGE φA VOLTS	VOLTAGE φB VOLTS	VOLTAGE φC VOLTS	VOLTAGE φA-B VOLTS	VOLTAGE φB-C VOLTS	VOLTAGE φC-A VOLTS	CURRENT φA AMPS	CURRENT φB AMPS	CURRENT φC AMPS	WATTS/PHASE φA KWATTS	WATTS/PHASE φB KWATTS	WATTS/PHASE φC KWATTS	HARMONIC CONTENT (%) φA	HARMONIC CONTENT (%) φB	HARMONIC CONTENT (%) φC	VOLTAGE MODULATION (V) φA	VOLTAGE MODULATION (V) φB	VOLTAGE MODULATION (V) φC	DC CONTENT (MV) φA	DC CONTENT (MV) φB	DC CONTENT (MV) φC	FREQ. HZ	CONTACTOR VDC	GENERATOR EG	GENERATOR IG	TRANSIENT		
	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.3	.8	.6	.11	.15	56	55	55	[illegible]		268	69			
			31.	.75	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.5	1.2	4.2		.11	.16	42	35	49			273	58			
			[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.5	[illegible]	.6	.15	.19	.14	33	45	45			266	64			
			[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.8	1.8	[illegible]	.13	.10	35	32	45			257	81			
			[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	427	[illegible]	427	[illegible]	[illegible]	[illegible]	[illegible]	2.2	1.7	.15	.13	.13	32	32	45			292	111			
			11.	.95	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.3	.5	[illegible]	[illegible]	.10	44	30	30			258	61			
			[illegible]		101.1	111.5	112.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.6	[illegible]	.7	40	35	28			252	75			
			[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	40	[illegible]	30			242	140			
			[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	422	432	[illegible]	[illegible]	[illegible]	426	2.5	2.4	2.3	.1	.2	.2	60	30	30			283	196			

NOTES THIS DATA WAS TAKEN ABOUT 6 MONTHS EARLIER THAN THAT ON SHEETS 1&2. GENERATOR SPEED WAS LIMITED TO 15K WHEN FINAL DATA WAS TAKEN
OUTPUT VOLTAGE WAS SET AT ABOUT 115V WHEN THIS DATA WAS TAKEN

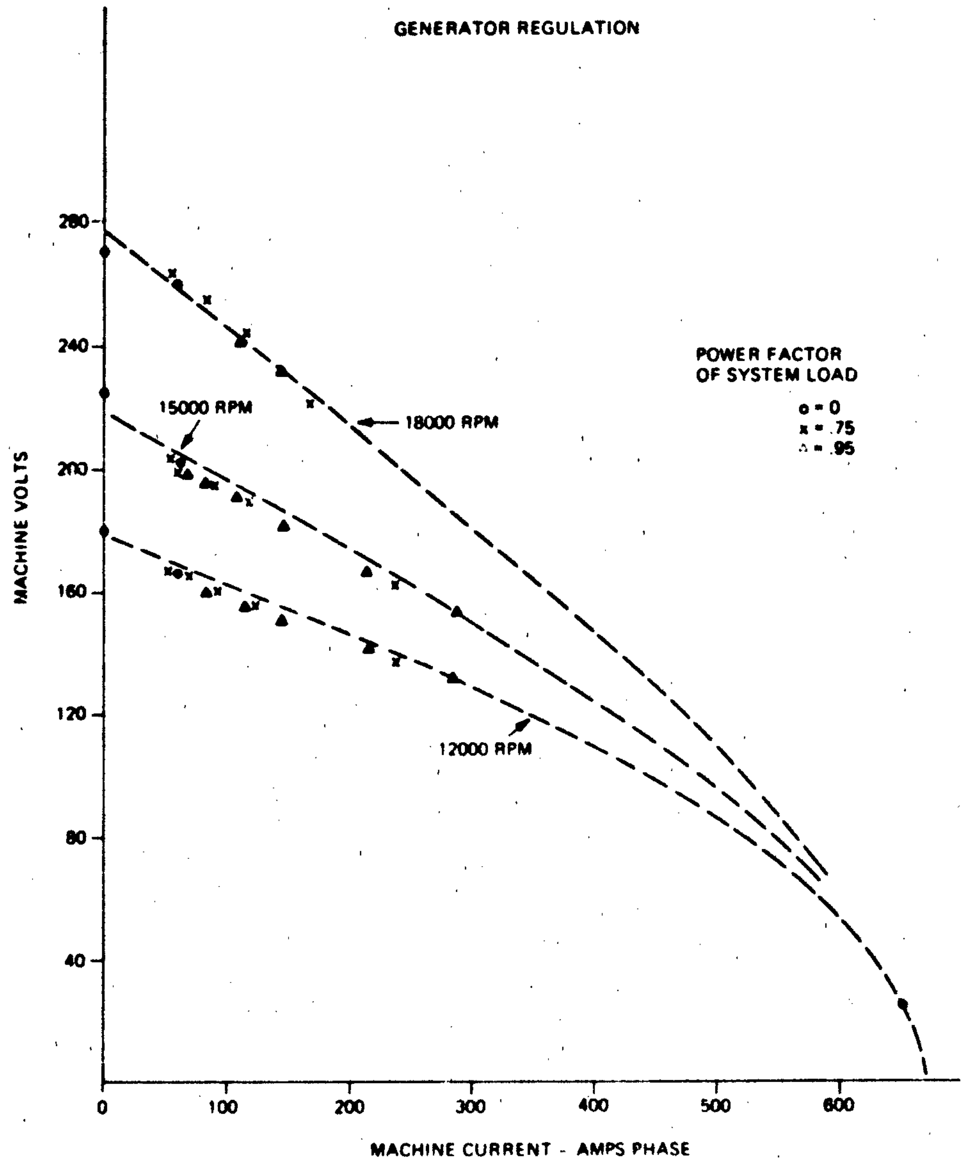


Figure 82. Generator Regulation In System

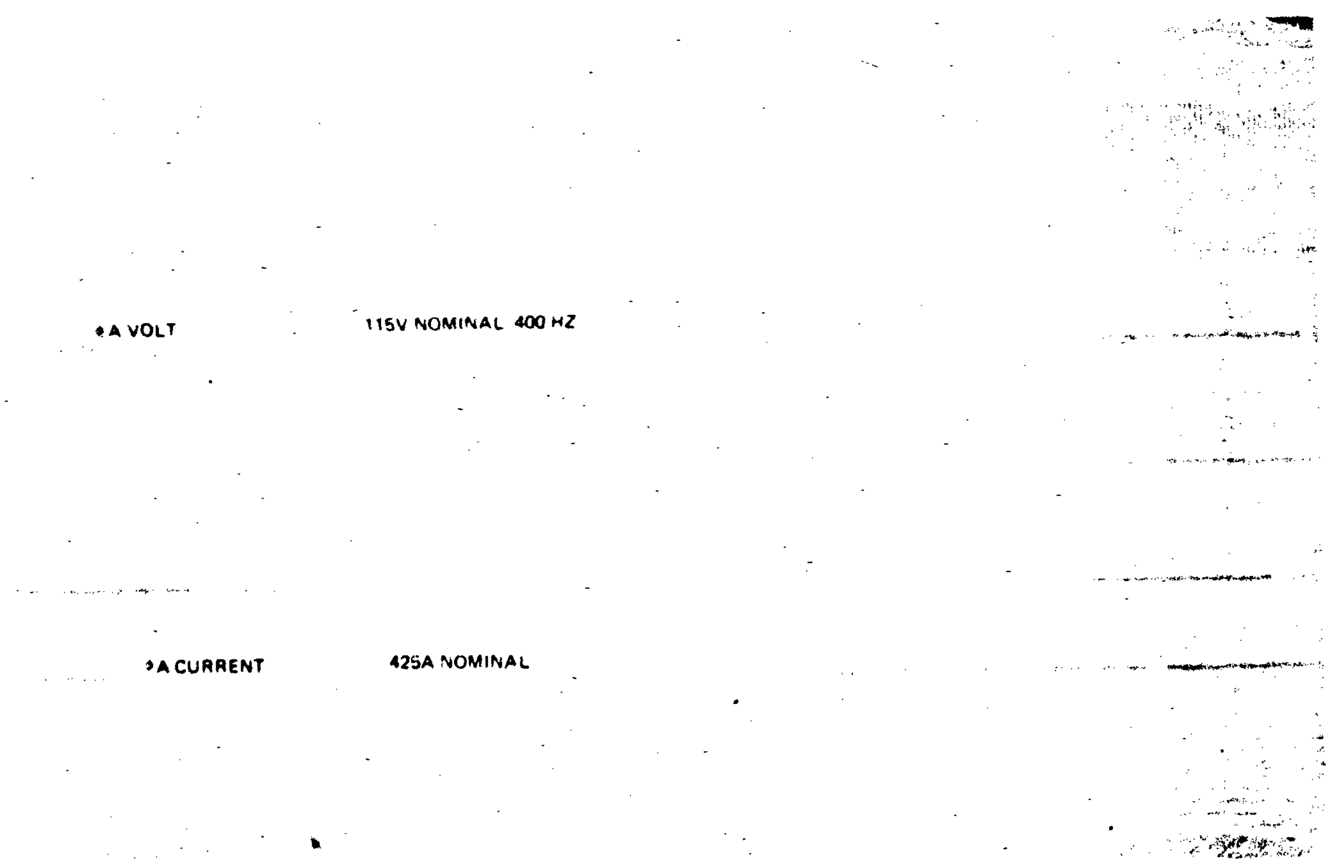


Figure 83. Transients - 150KVA, 12,000 RPM, .75 Pf and 27 Oct 77

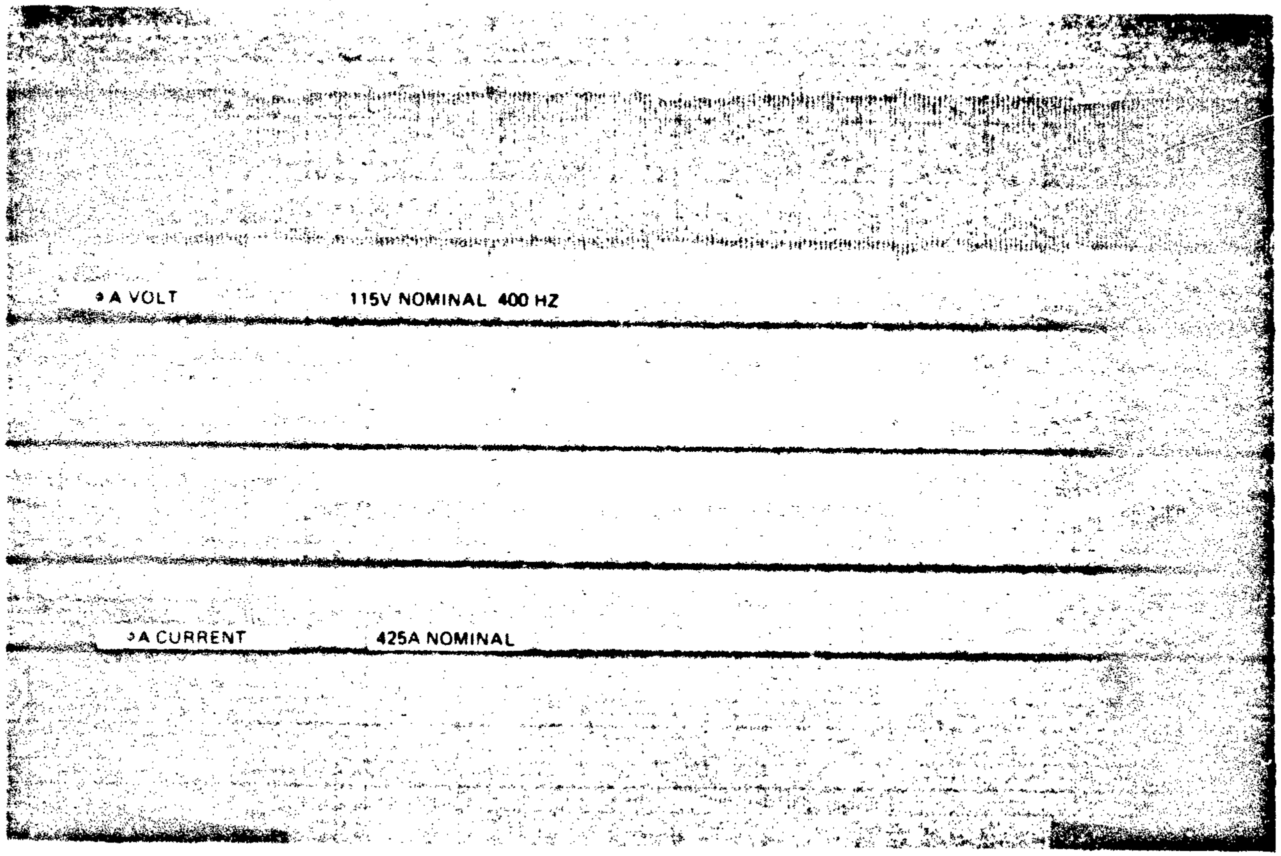


Figure 84. Transients - 150KVA, 12,000 RPM, .95 Pf and 27 Oct 77

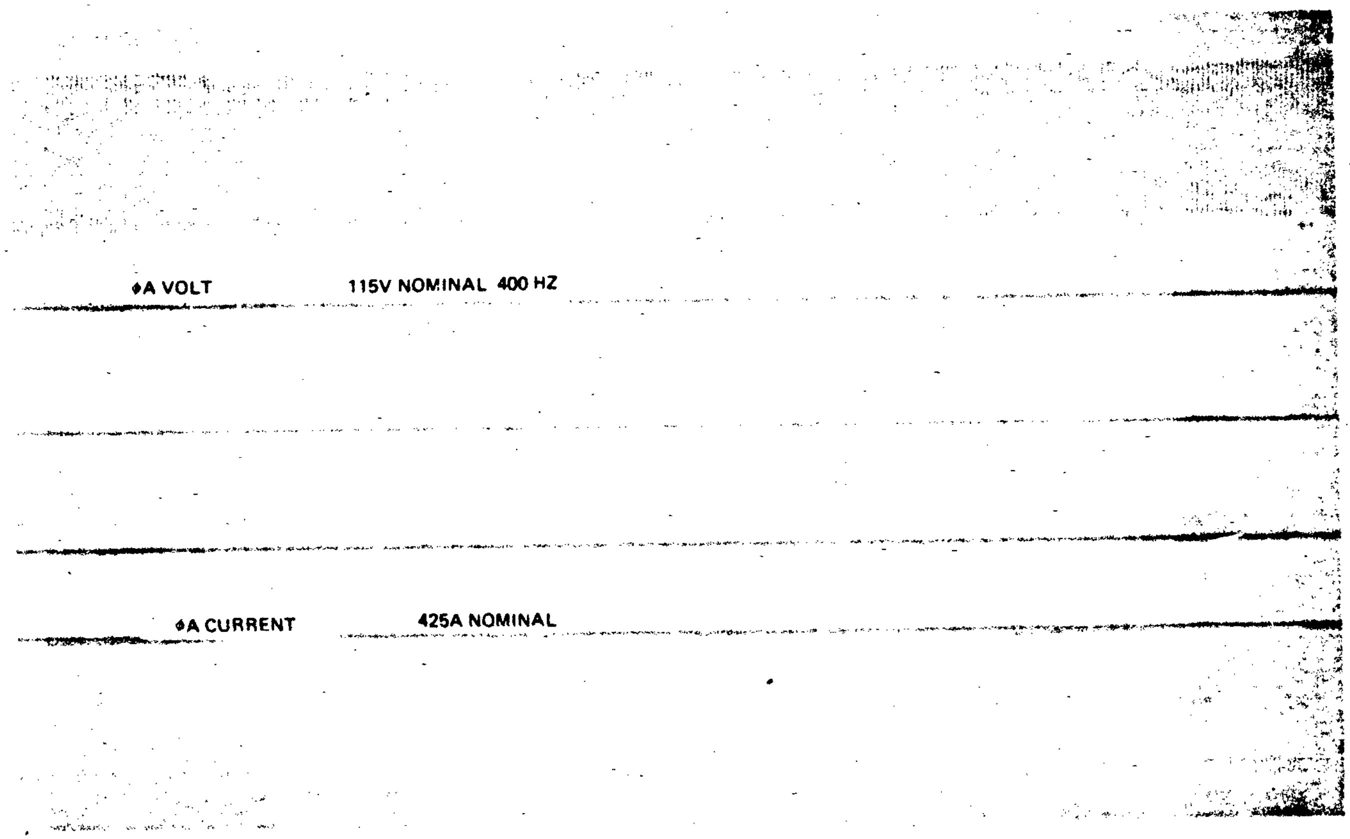


Figure 85. Transients - 150KVA, 15,000 RPM, .75 Pf and 27 Oct 77

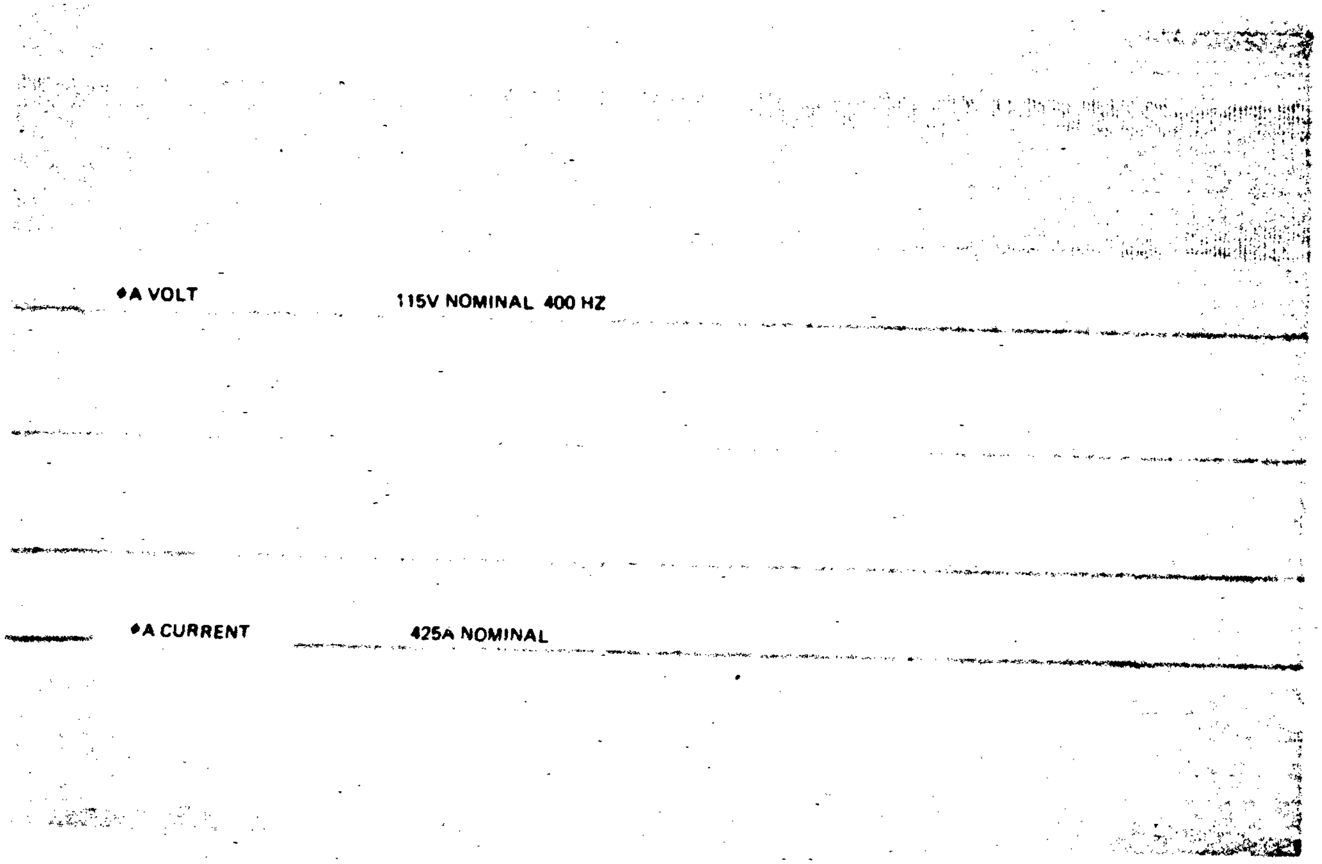


Figure 86. Transients - 150KVA, 15, 000 RPM, . 95 Pf and 27 Oct 77

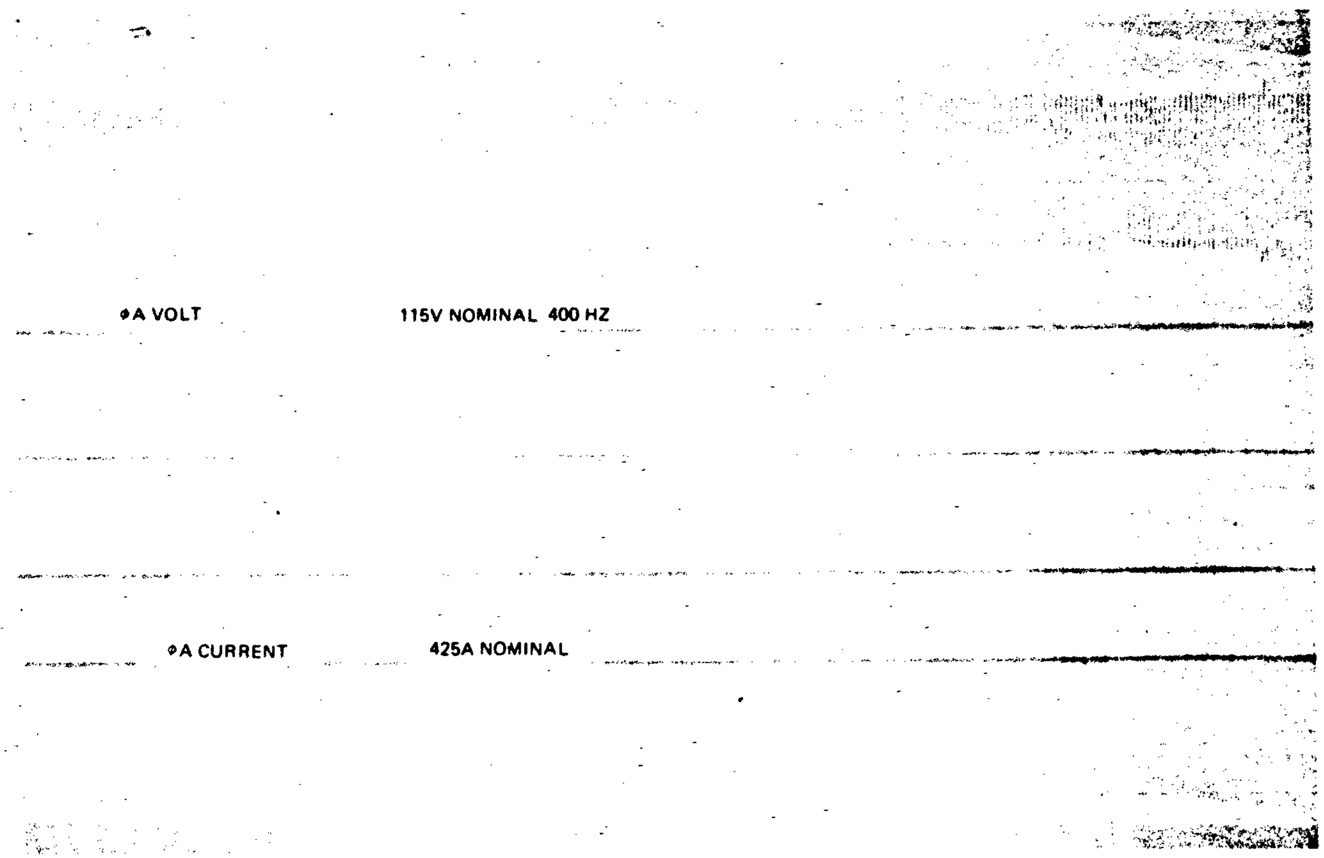


Figure 87. Transients - 150KVA, 18,000 RPM, .75 Pf and 27 Oct 77

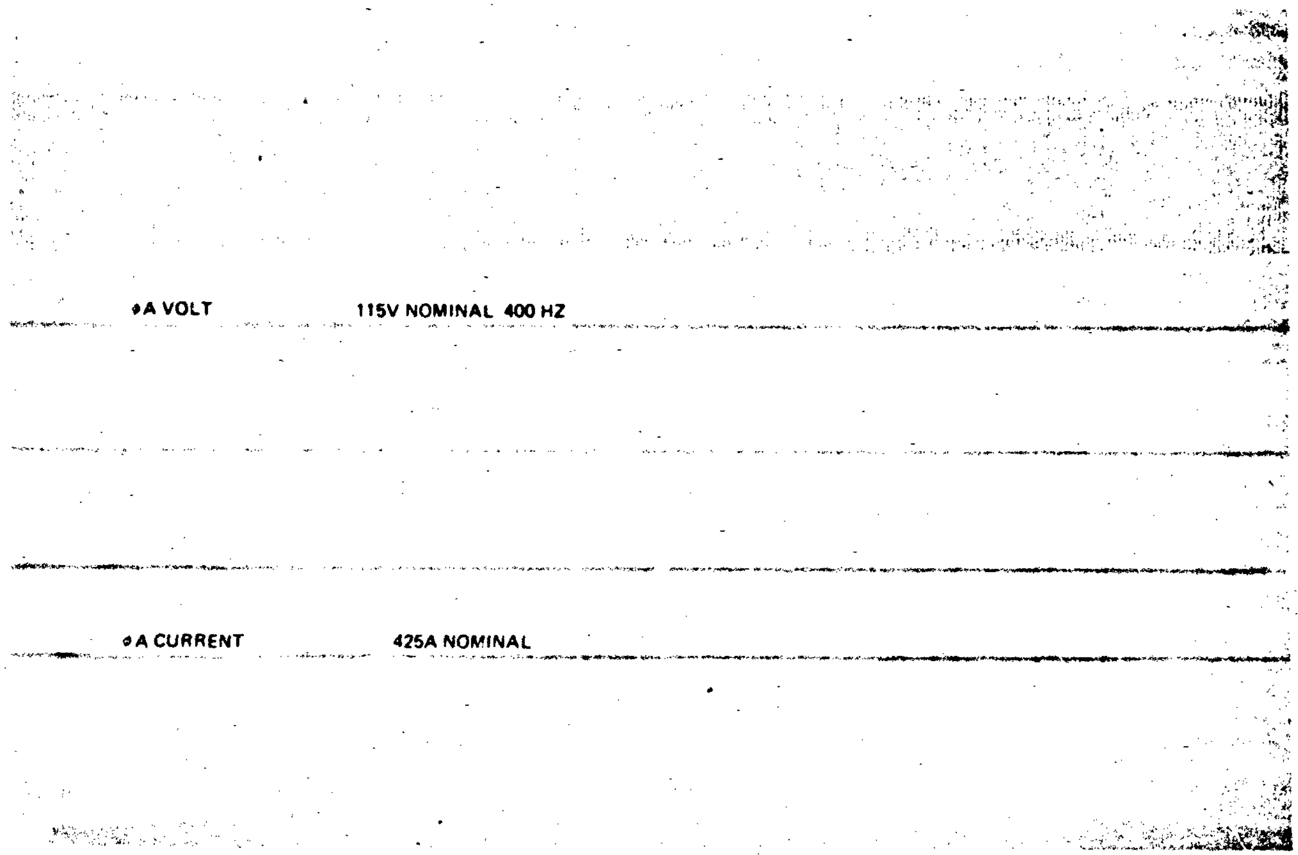


Figure 88. Transients - 150KVA, 18,000 RPM, .95 Pf and 27 Oct 77

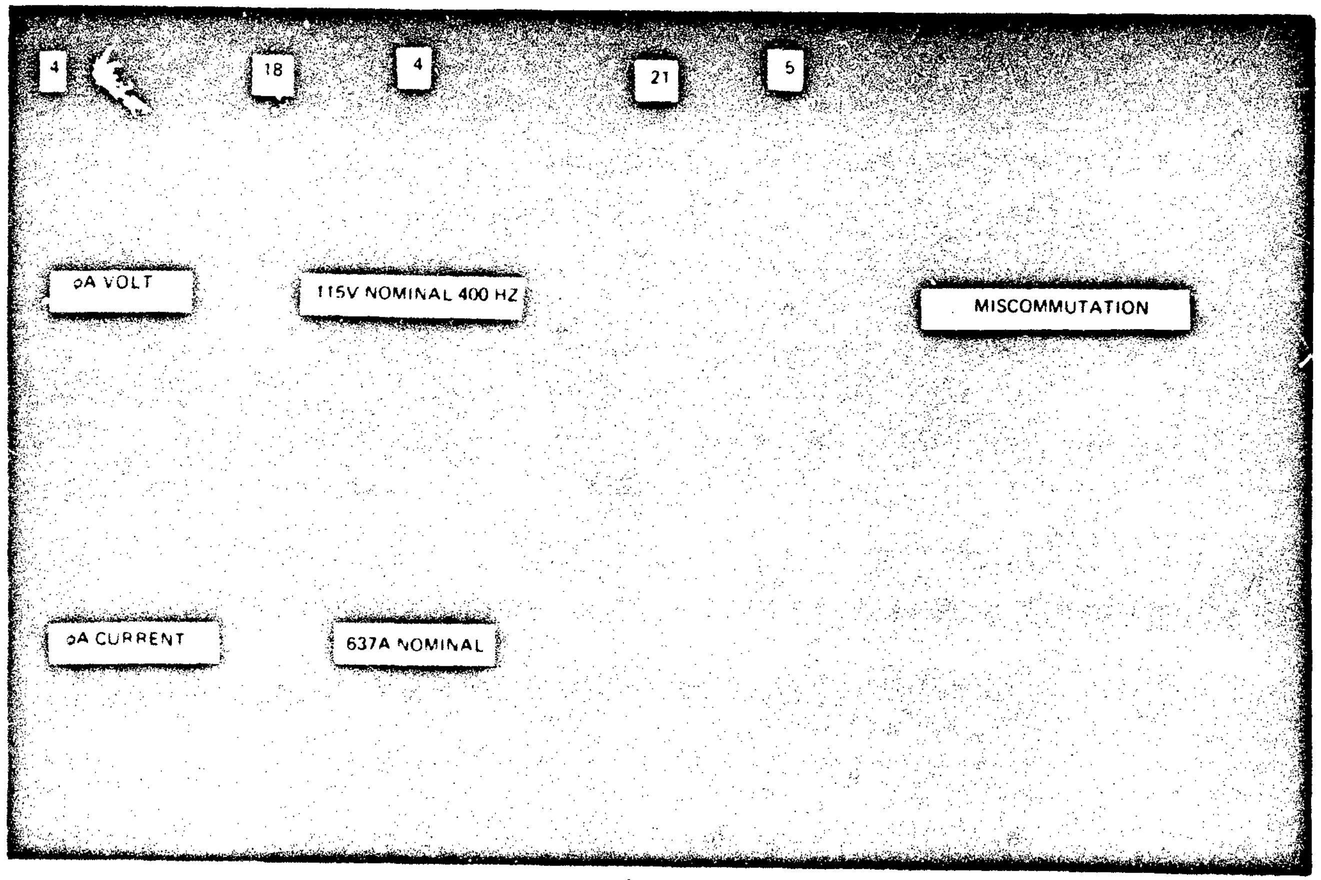


Figure 89. Transients - 225KVA, 12,000 RPM, .75 Pf and 28 Oct 77

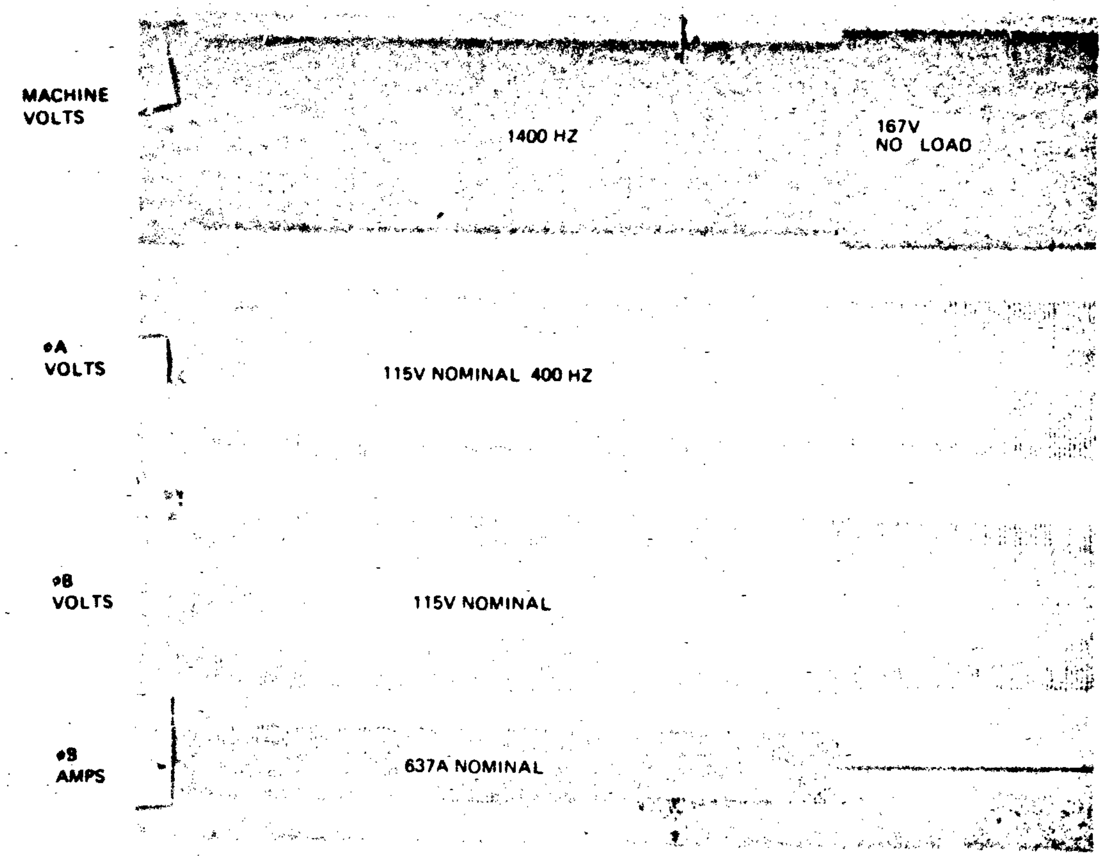


Figure 90. Transients - 225KVA, @.85 Pf, 12,000 RPM and 20 Mar 78

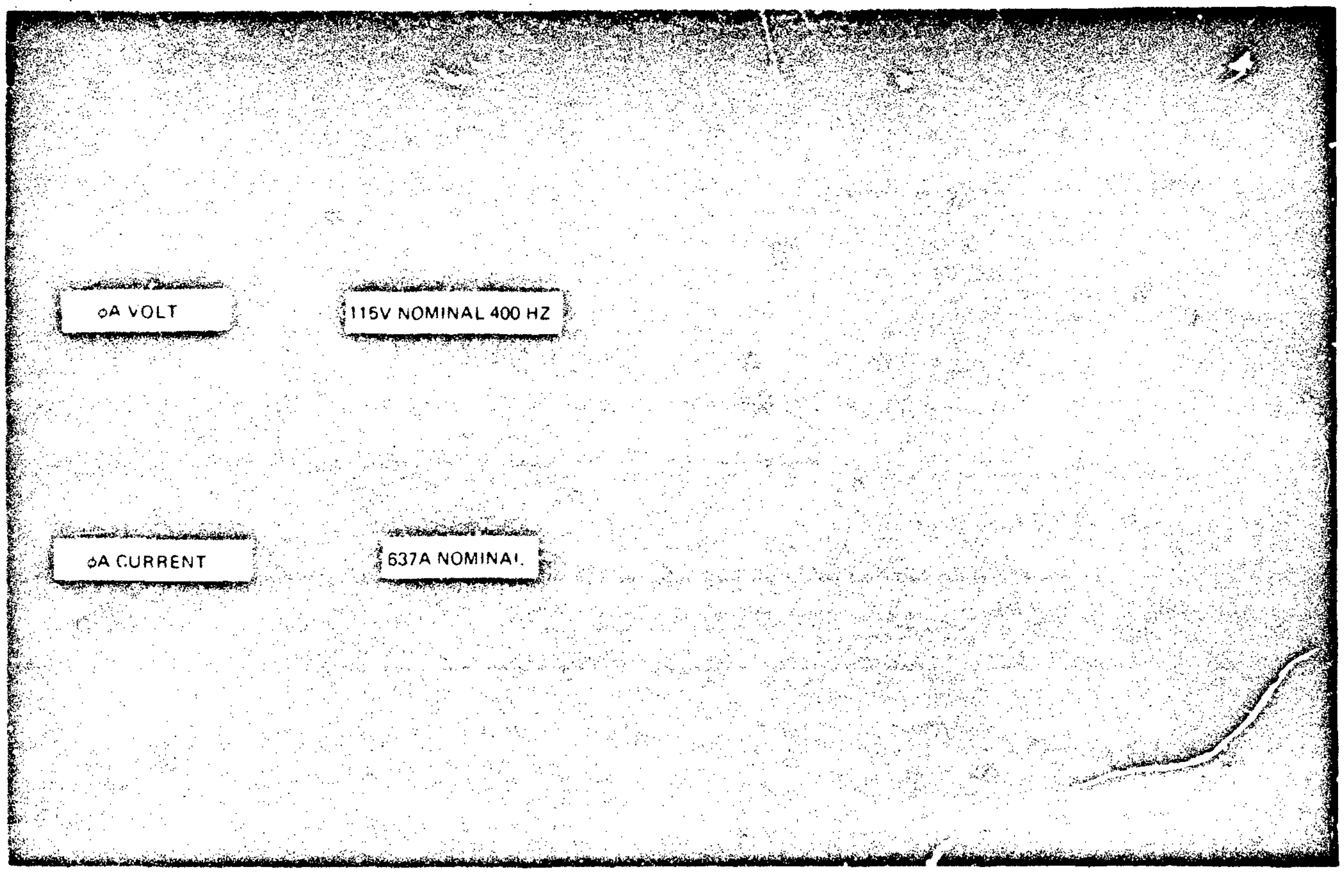


Figure 91. Transients - 225KVA, 15,000 RPM, .75 Pf and 28 Oct 77

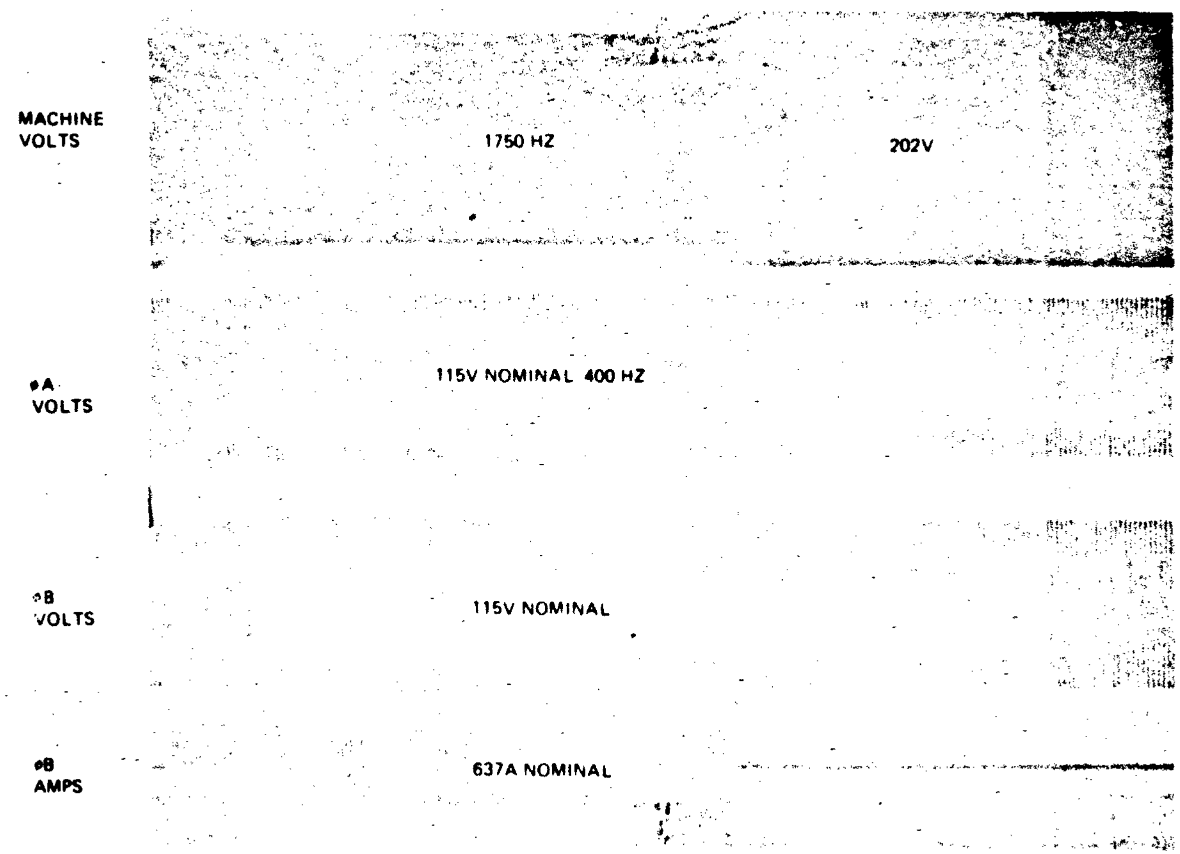


Figure 92. Transients - 225KVA, @.95 Pf, 15,000 RPM, and 20 Mar 78

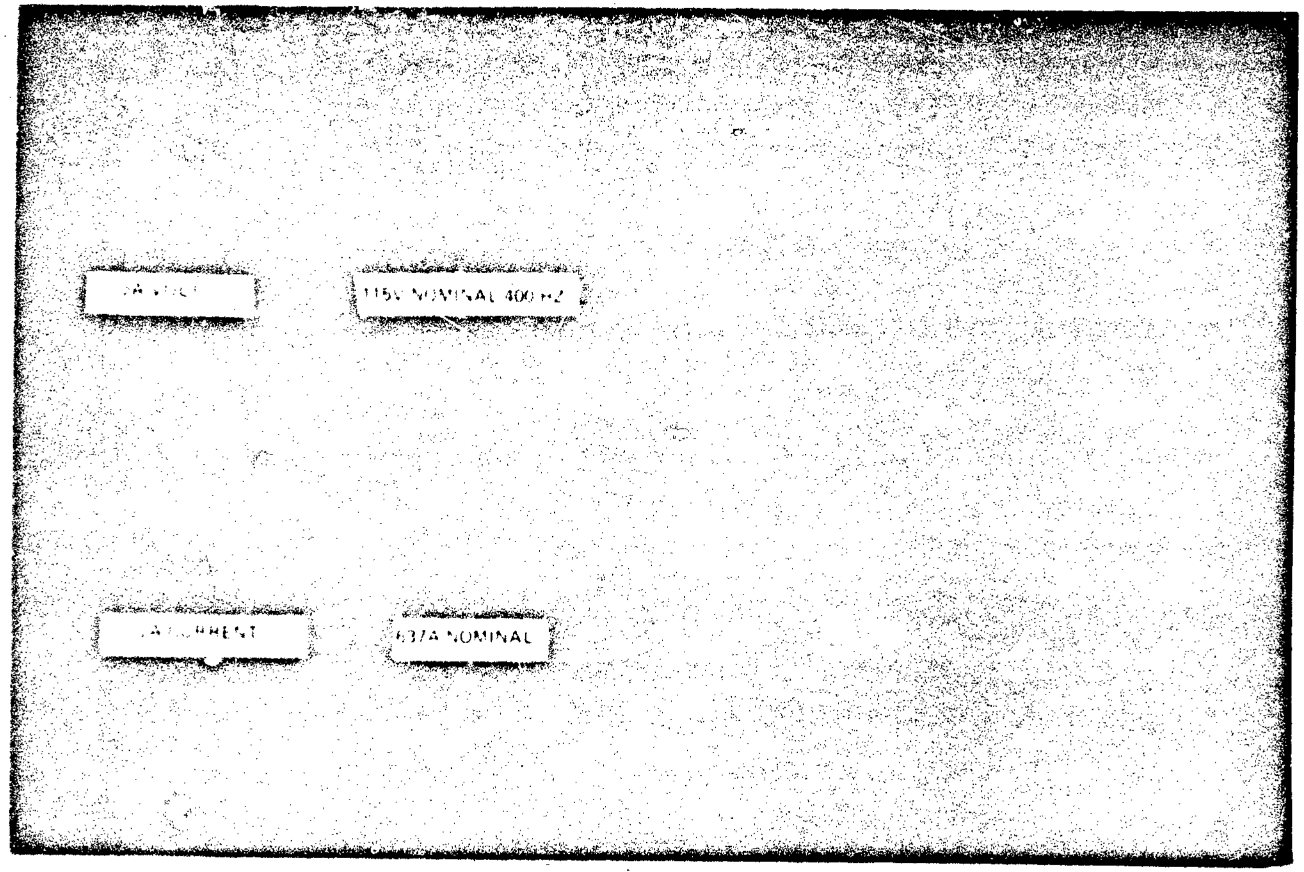


Figure 93. Transinets - 225KVA, 18,00o RPM, .75 Pf and 28 Oct 77

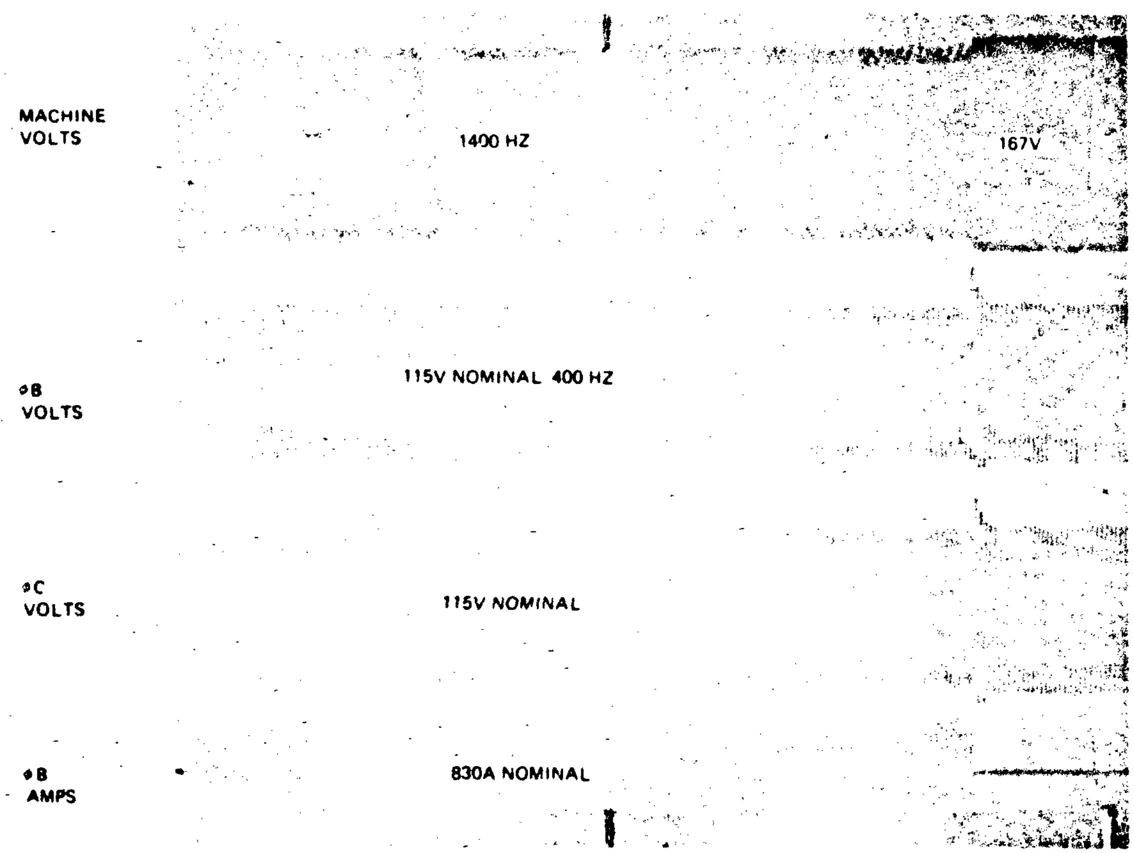


Figure 94. Transients - 300KVA, @12, 000 RPM, .75 Pf and 17 Mar 78

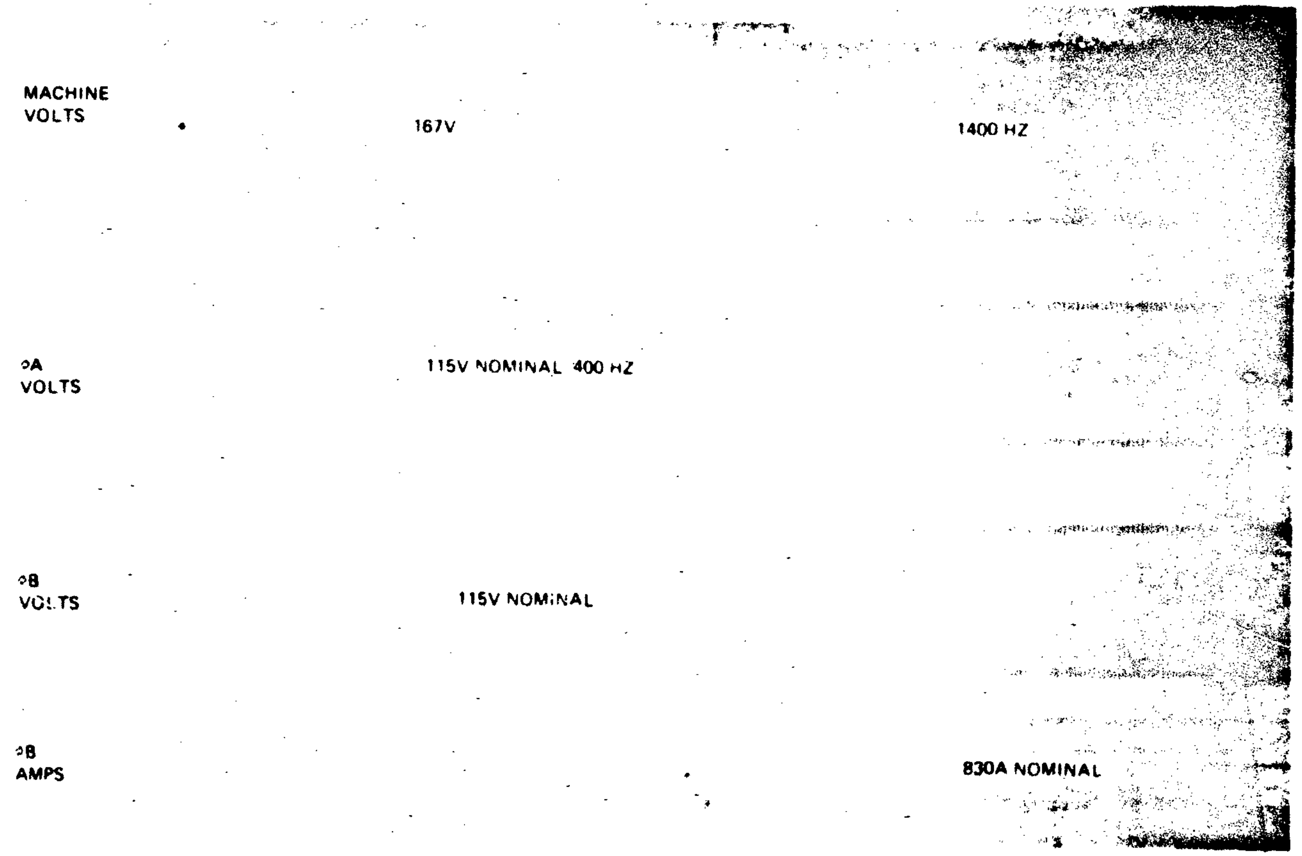


Figure 95. Transients - 300KVA, 0.95 PF, 12,000 RPM and 20 Mar 78

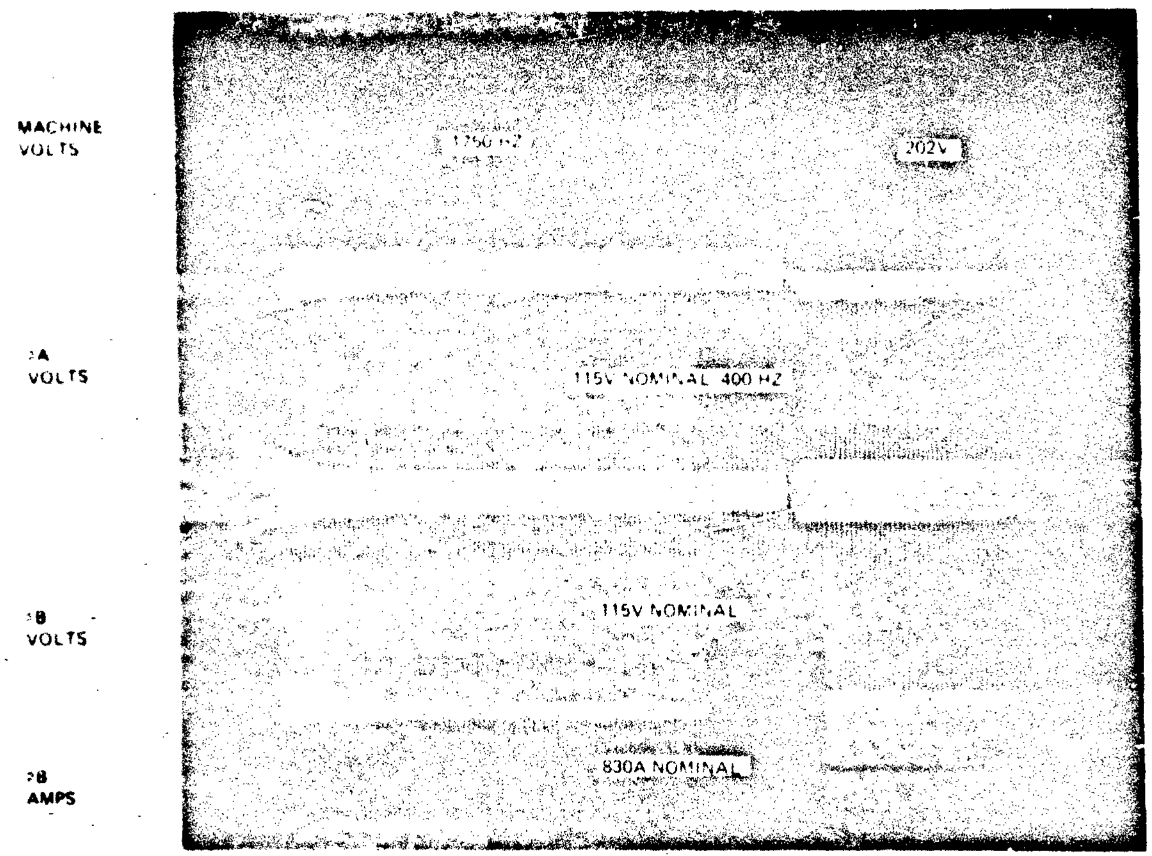


Figure 96. Transients - 300KVA, @.75 Pf, 15,000 RPM and 17 Mar 78

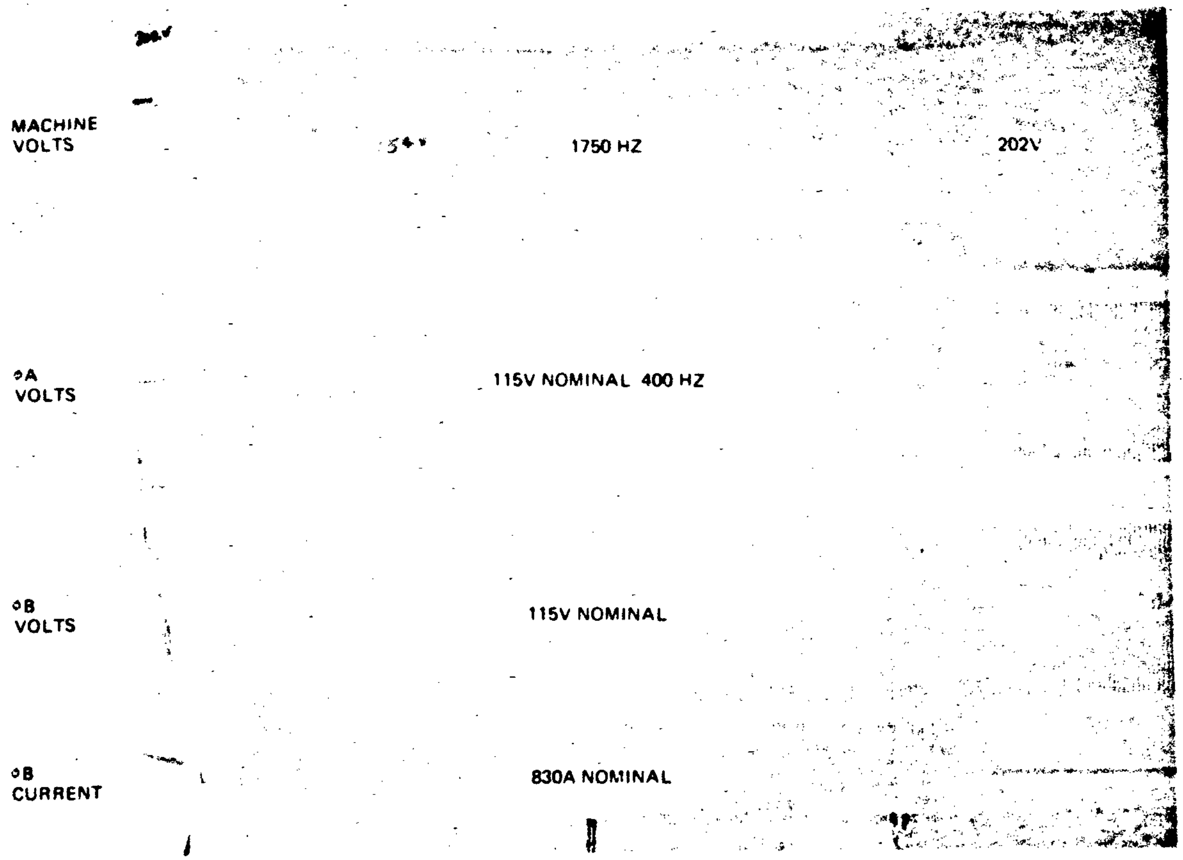


Figure 97. Transients - 300KVA, @.95 Pf, 15,000 RPM and 20 Mar 78

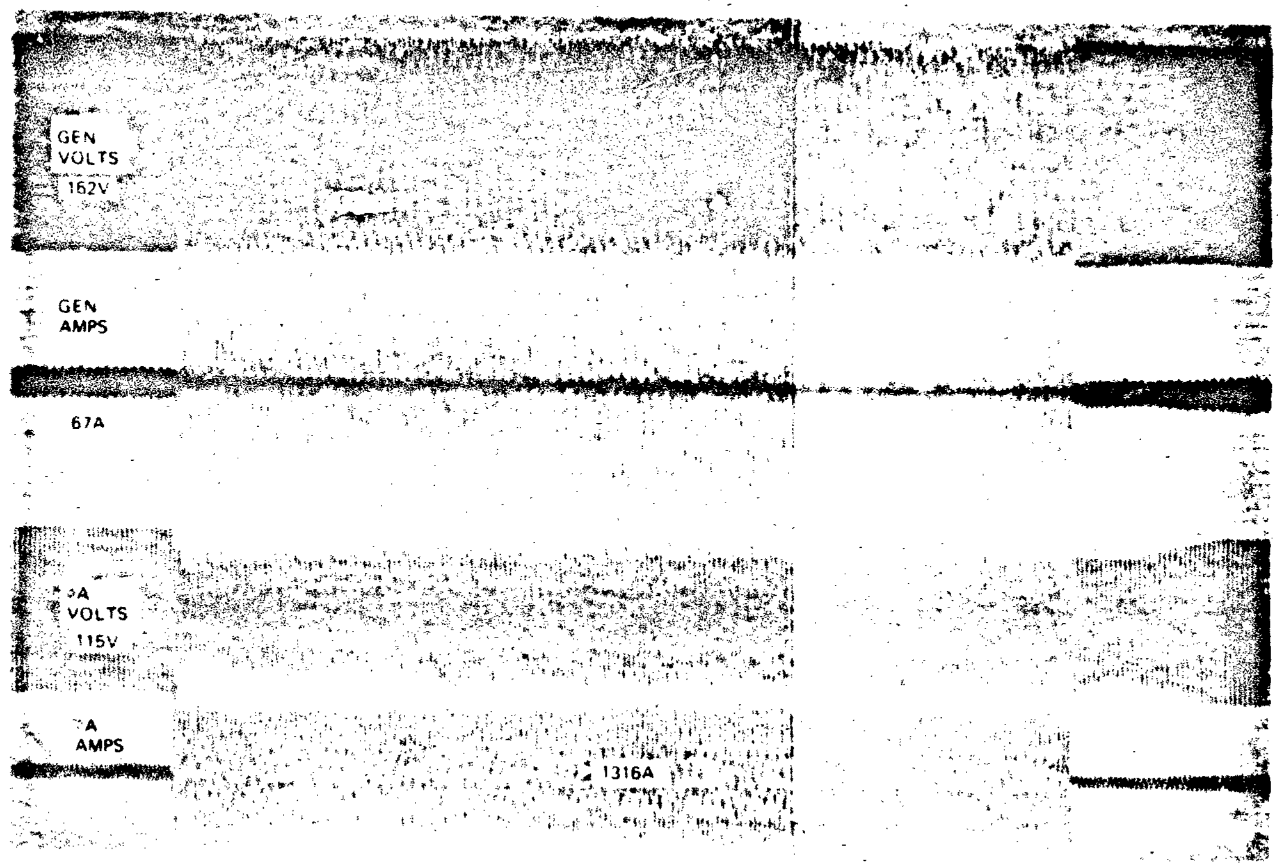


Figure 98. Fault - A-N, 12,600 RPM

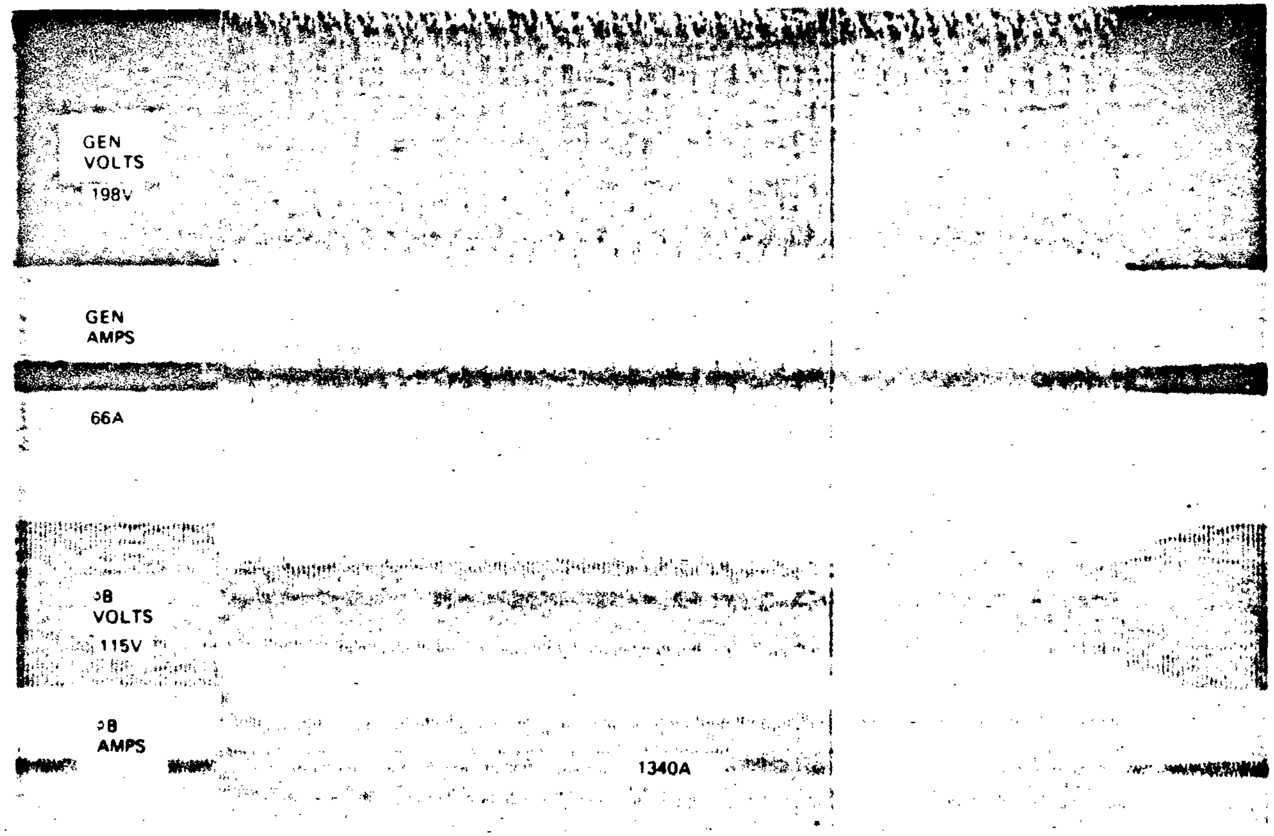


Figure 99. Fault - B-N 15,000 RPM

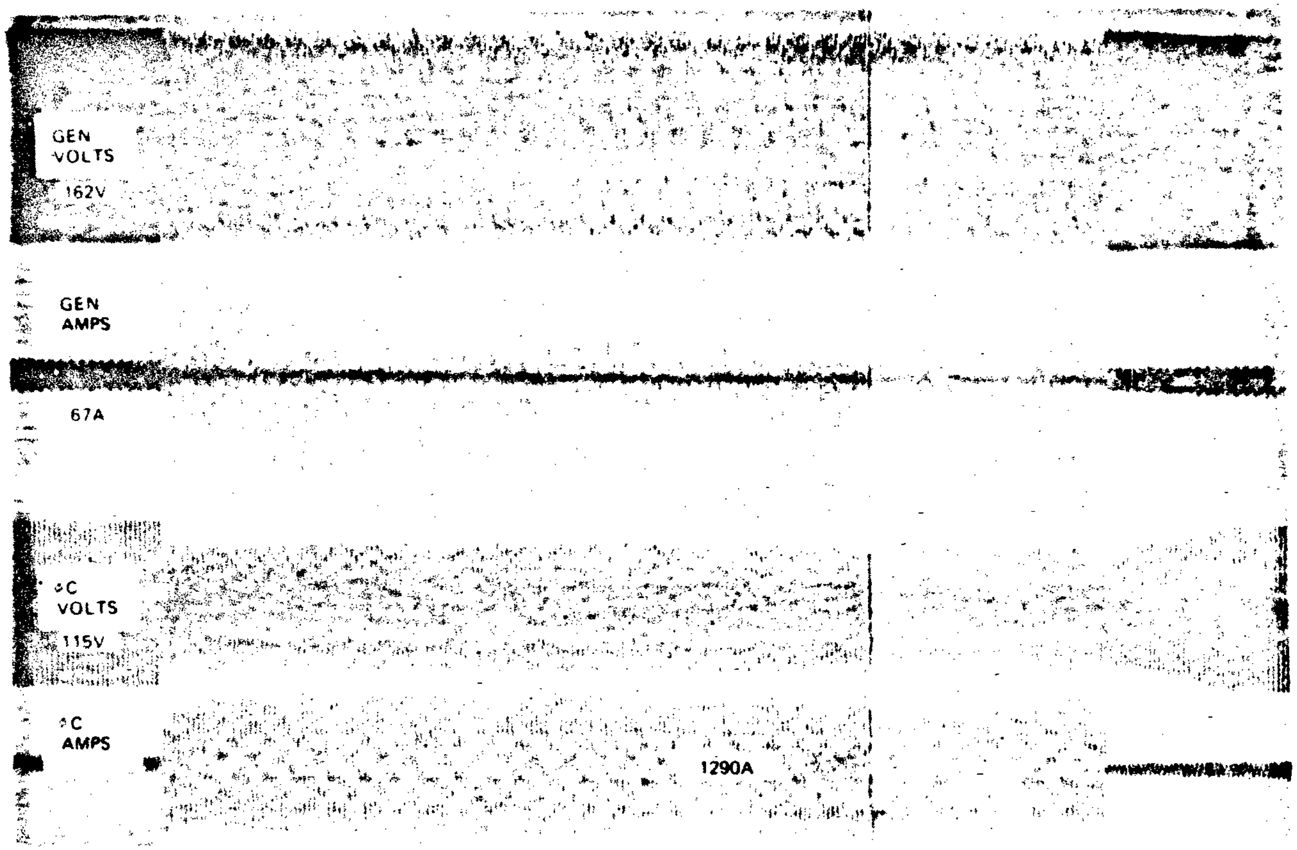


Figure 100. Fault - C-N 12,000 RPM

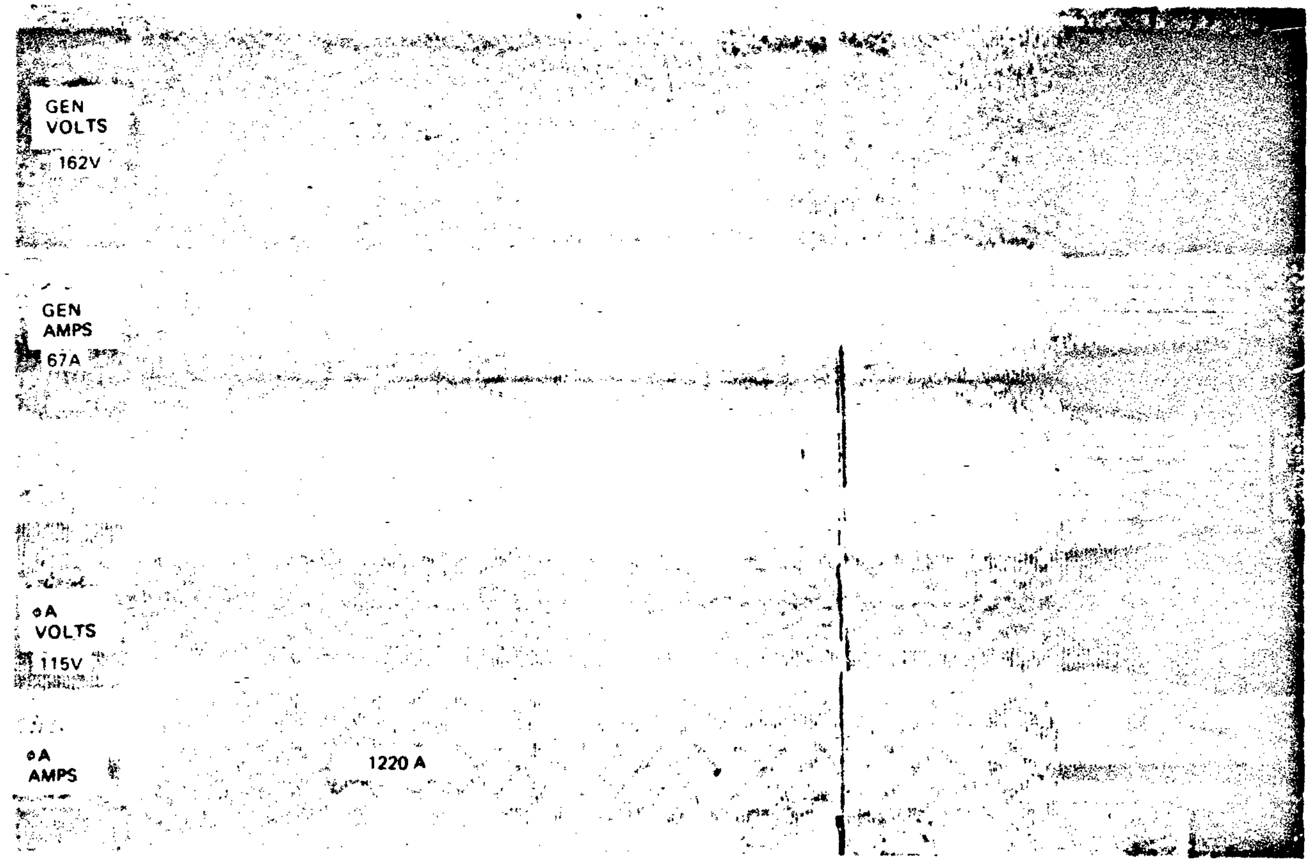


Figure 101. Fault - A-C 12, 000 RPM

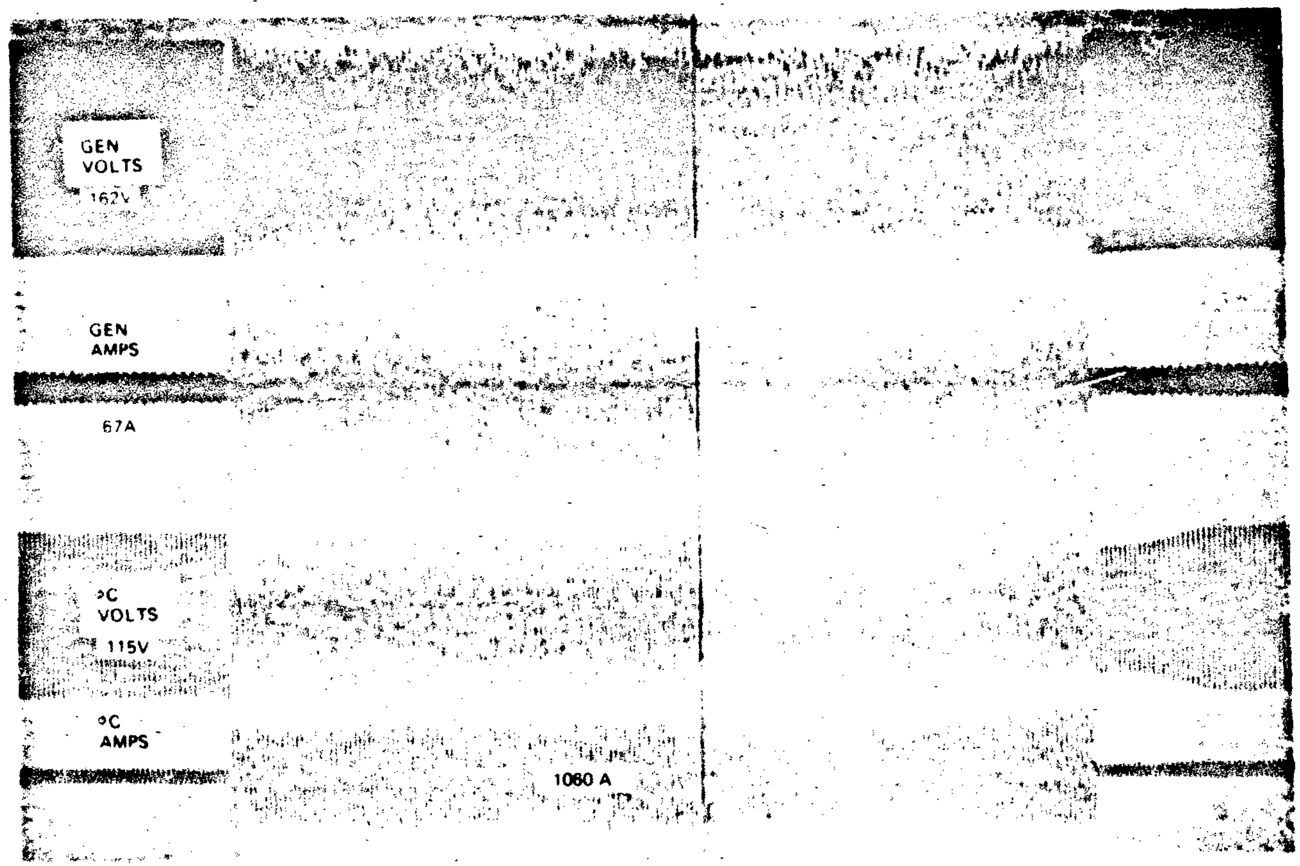


Figure 102. Fault - B-C 12,000 RPM

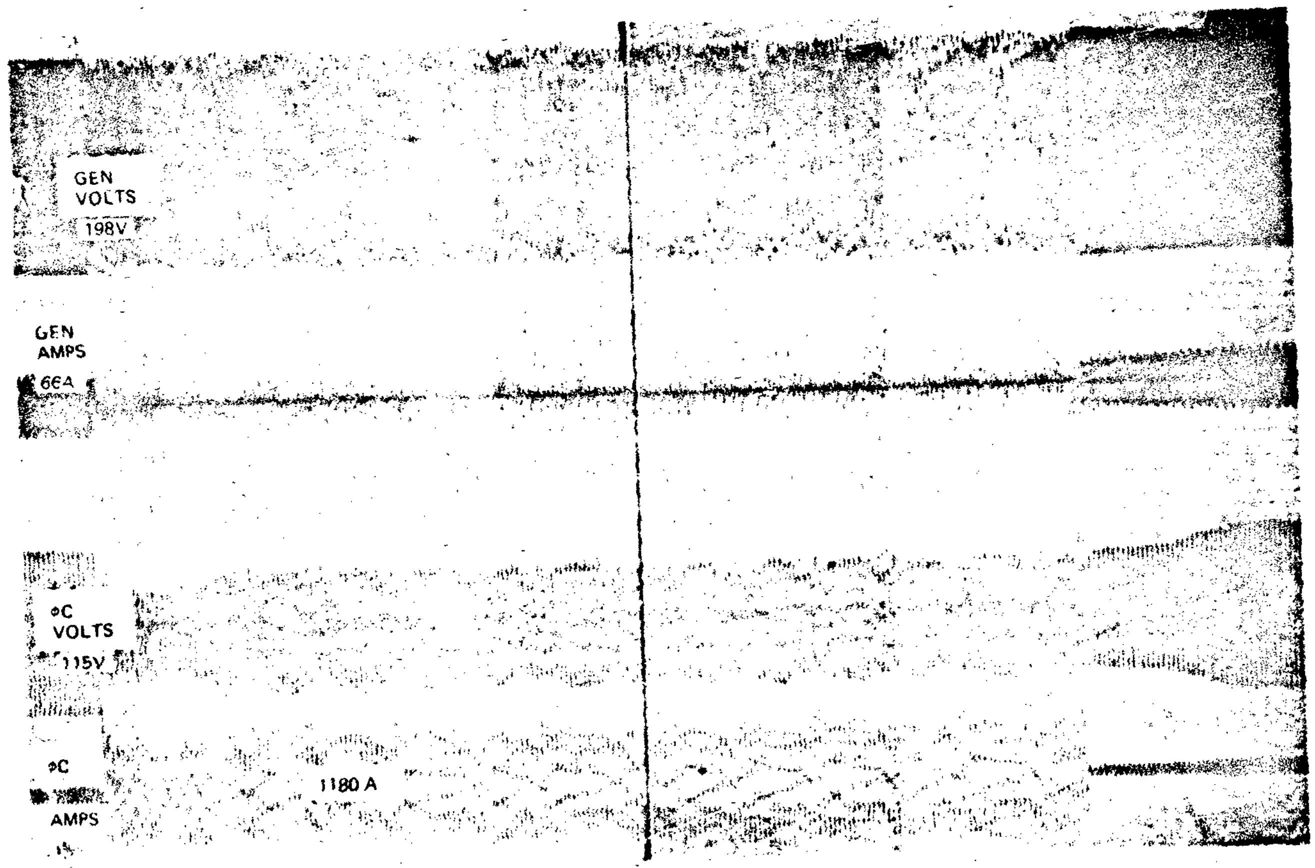


Figure 103. **Fault - B-C 15,000 RPM**

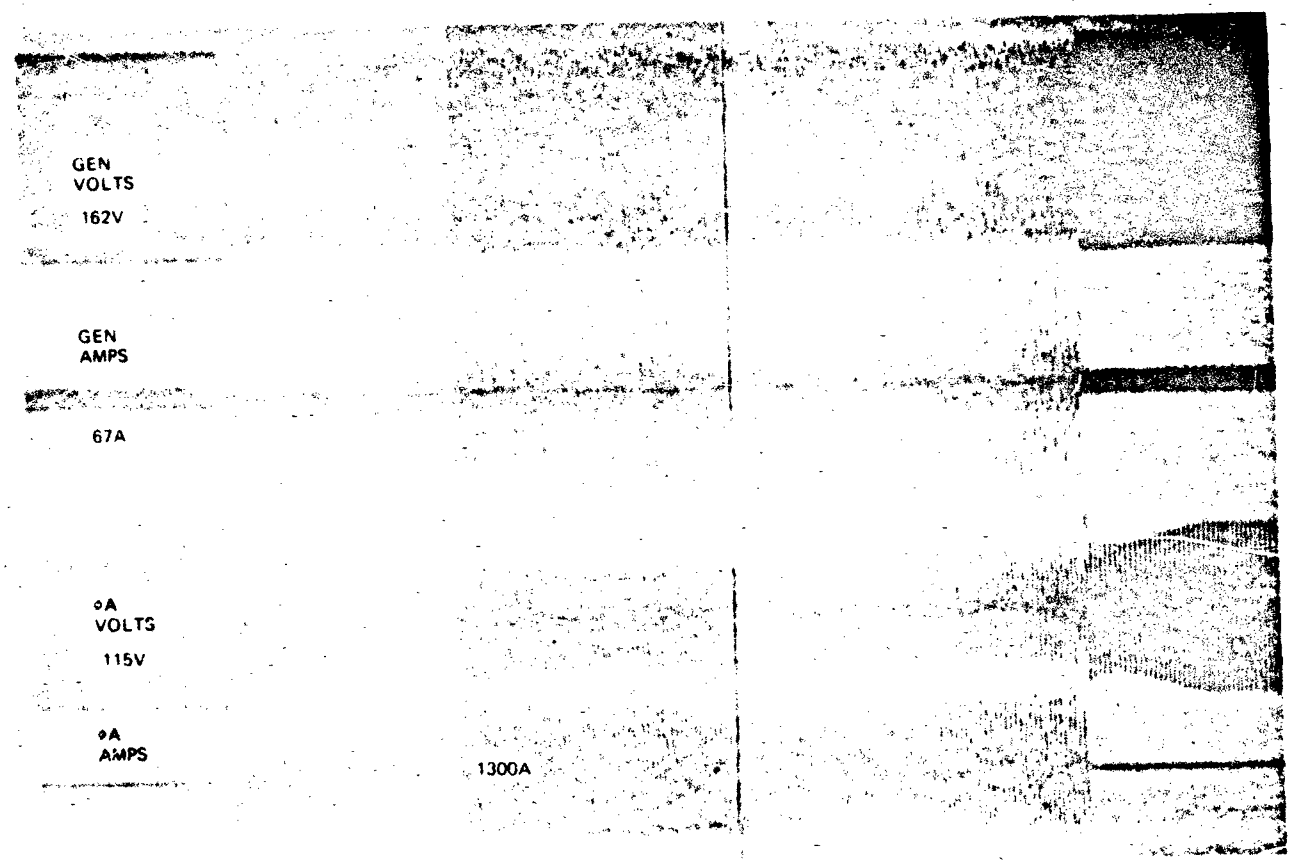


Figure 104. Fault - A, B, C - N 12,000 RPM

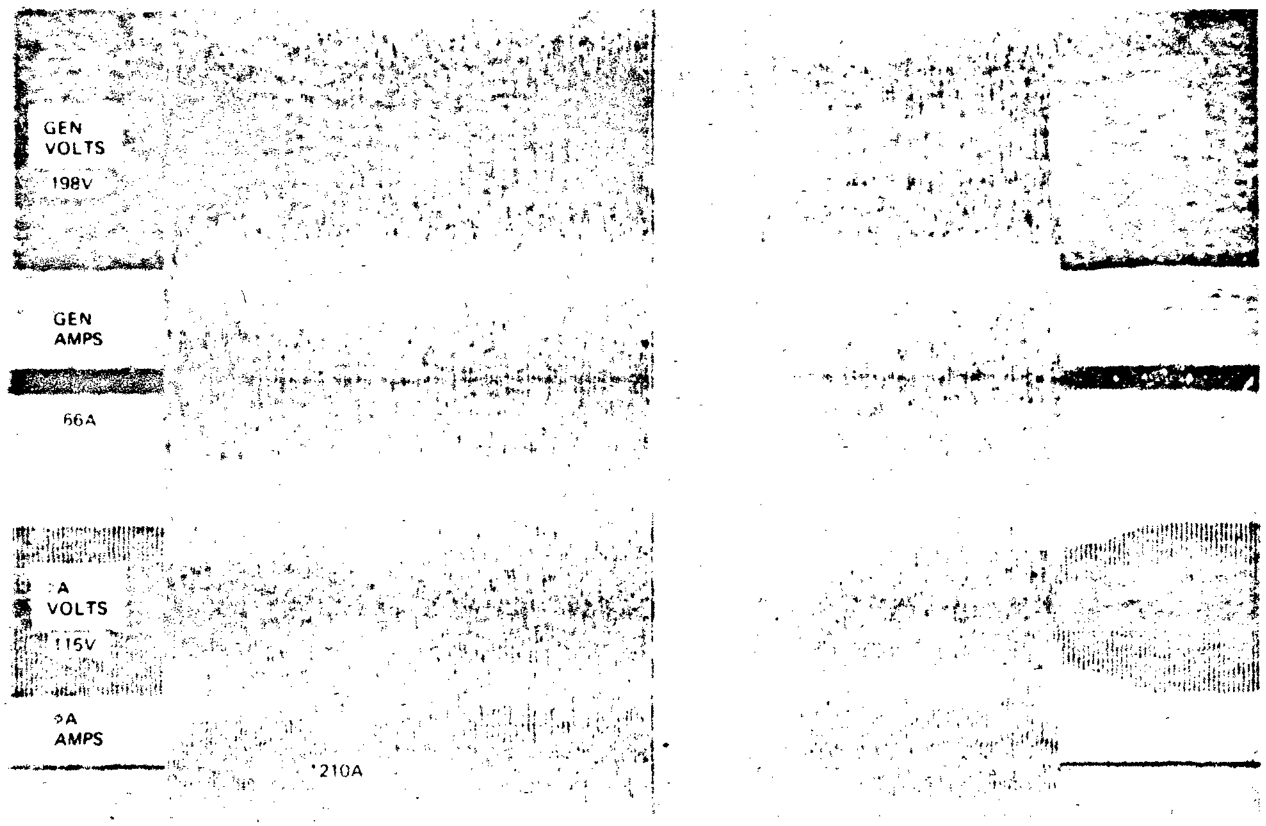


Figure 105. Fault - A, B, C 15,000 RPM

TABLE 6

FAULT PERFORMANCE

Gen RPM	Fault	Current A	Current B	Current C
12,000	A-N	1310		
	B-N		1300	
	C-N			1290
	A-B	1210	1150	
	B-C		1110	1060
	C-A	1220		1160
	ABC N	1300	200	160
	ABC	1230	720	550
15,000	AN	1320		
	B-N		1340	
	C-N			1280
	A-B	1250	1150	
	B-C		1210	1180
	C-A	1260		1180
	A-B-C-N	1330	300	100
	A-B-C	1210	680	600

TABLE 7

TESTS OF PROTECTIVE FUNCTIONS

Function	Trip Level	Specification
Overvoltage (OV) (V)	123.5 ultimate 120ms with 135V	125 ultimate 2.3 sec with 135V
Differential Fault (AMPS) High Frequency (DH)	85	57
Differential Fault (AMPS) 400Hz (DL)	120	152
Generator Overcurrent (AMPS) (GOC)	115	-
DC Content (V) (DC)	+.445, -.437 .8 sec with 1.5	+.55 1 sec with 1.5
Undervoltage (V) (UV)	98	90-110
Zero Sequence Voltage (V) (ZV)	4.1	4.25 + 1
Wrong Frequency (HZ) (WF)	385.9 - 412.5	385 - 415
Waveform Distortion (WD)	7.5V @ 2kHz	9.2V
Auto Parallel (V) (AP)	5	-
Difference Load Current (AMPS) (DLC)	91 Amps	-
Start Cutout (SCO)	1259Hz - 10,800 RPM	11,000 ± 333 RPM
Underspeed (US)	Pickup 1387Hz = 11,880 RPM Dropout 1329Hz = 11,390 RPM	11-12,000 RPM

TABLE 8

150 KVA PMG SYSTEM EFFICIENCY SPEED 12K RPM

Nominal Load		Output KW				Torque in *	Mech KW	Eff %
		A	B	C	Total			
KVA	PF							
OFF						52.5	7.5	
NL		0	0	0		85	12.1	0
37.5	.75	10.5	9.7	10.6	30.8	295	41.9	73.5
75		19.2	19.2	19.3	57.7	482	68.5	89.2
112.5		27.9	27.8	28.2	83.9	682	96.9	86.6
150		37.9	37.6	37.9	113.4	907	128.8	88.0
37.5	.95	12.0	13.7	11.6	37.3	342	48.6	76.7
75		24.2	24.0	24.2	72.4	602	85.5	84.7
112.5		35.5	34.9	34.9	105.3	847	120.3	87.5
150		46.9	47.8	47.2	141.9	1137	161.5	87.9

6.2.2 START MODE TESTING

Two drive stands are required for start mode testing. One drive powers a 150 KVA wound rotor motor machine VSCF system which was used as the 400Hz power supply. The second drive provides the mechanical loading for the PM system which is now functioning as a brushless motor.

Even though performance was not optimized, the basic ideas were proven. These were:

1. The system would operate satisfactorily in a quasi three phase mode during the low speed period, where commutation by the supply is assured, with little loss of torque.
2. The phase lock loop accurately defines all 9 phase conduction intervals with only three phase position sensing. The phase lock loop performs the phase advance with speed function very satisfactorily.
3. Indirect field weakening of the permanent magnet machine by phase advance works just as predicted.
4. The superior cummutating capability of the nine phase machine was demonstrated. Much more torque per system KVA was achieved at the high speed and with 1.1 PU current than a 6 phase system delivered with 1.5 PU current.

Figure 86 and Table 8 show the performance in start mode. Figure 34 shows the starter accelerating a two ton flywheel. The data in Table 8 was taken statically with the PM drive stand braking the starter at set constant speeds. Table 8 shows efficiency data calculated from the data taken statically.

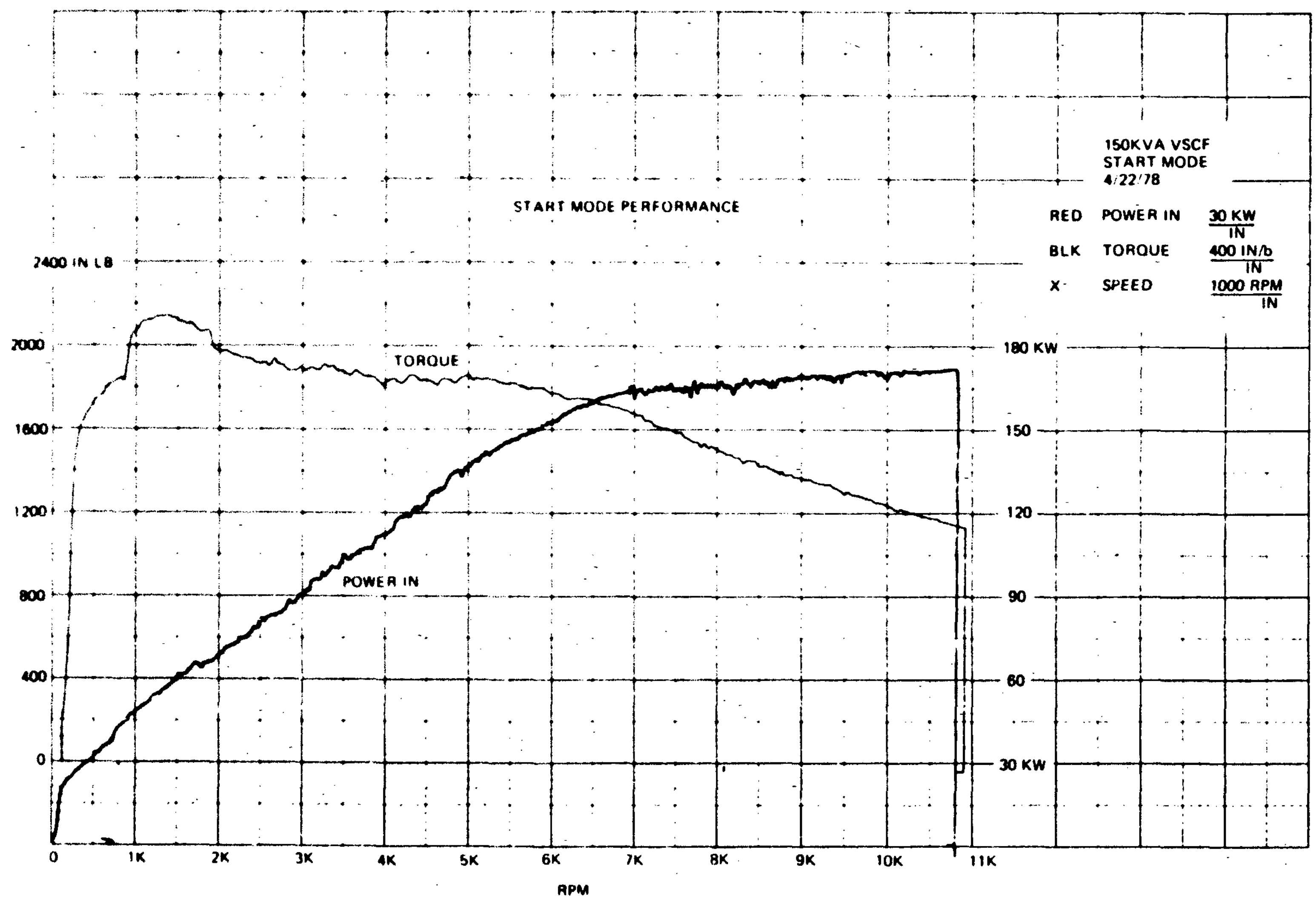


Figure 106. Start Mode Performance

TABLE 9

STEADY STATE START DATA

RPM/100	Torque Out In/#	Torque Out Ft/#	Input Amps	Input Volts	KW Ph	IN Total	Power Factor	Mech KW Out	Efficiency %
0	1750	146	450	98	7.7	23.1	.18	0	0
12	2000	167	470	98	16.9	50.7	.37	28.5	56
24	1960	163	460	98	26.6	79.8	.59	55.6	70
36	1820	152	470	95	31.2	93.6	.7	77.7	83
48	1700	142	490	116	43.2	130	.76	96.8	74
60	1630	138	490	116	49.3	148	.87	118	80
72	1580	132	511	115	54.5	163	.92	135	83
84	1390	116	500	113	54.4	163	.93	138	85
96	1240	104	510	115	55	165	.94	142	86

Problem Areas in Start Mode

Four areas were addressed during this test period

1. Noise in the position sensors and phase lock loop. A major portion of the available test time was used trying to suppress noise problems. Noise related problems are to be expected since the basis of the system involves switching hundreds of amps at high voltage with steep wavefronts, while the output of the Hall probes used to sense rotor position is only 10's of millivolts.

   The Hall probes sensing rotor position are mounted at the anti-drive end of the rotor where they sense leakage flux. By mounting them below the shrink ring, position errors caused by non-uniform shrink ring segments are avoided. The negative feature is very low flux density compared with that of the normal air gap and hence reduced probe output. Probe outputs of about 50mV peak were observed which is equivalent to flux density of 2-2.5Kg. Three or four times higher probe voltages were available in an earlier wound rotor prototype where the probes were mounted on a stator tooth.

   This low signal level aggrevated the noise problems. Some poor connections in the twisted shielded pair lines from machine to converter were also found. Finally layout of the printed board was not good with long runs of the low input signal from the sensors close to digital signals.

   The system was made workable by putting large hysteresis in the comparitors sensing the probes and by adding filtering.

2. The next step was setting the position sense and phase advance with speed. This was done by manually rotating the position sense assembly in the machine and testing for torque and commutation versus speed and current. From this data a sense assembly setting was chosen and a linear advance vs. speed function was added. Somewhat more torque can be achieved with a more complex advance vs speed function.

3. Next the current control dynamics were adjusted. A considerably slower than desired current loop was used because of a transient experienced at the three to nine phase mode shift. An improved system would gradually shift the phase of the current in the six machine phases which are forced out of position in the three phase mode. A circuit design, completed since the test period, indicates this can be readily accomplished with a circuit requiring no more parts than the original.

4. The final problem area is interaction with the 400Hz power source which in this case was a second 150 KVA VSCF system. The load presented by the starting system is a severe one. The power factor varies from almost zero lagging at the beginning of the start to slightly leading during the field weakening period at the end of the start. The current drawn also contains a very high harmonic content. We are able to operate at 1.1 PU current rather than the 1.5 hoped for.

Figures 107 and 108 show system waveshapes at high and low machine speeds during start.

6.2.3 PARALLEL OPERATION TESTING

Limited testing of parallel operation was performed with both machines mounted on a single 300HP drive stand with slightly different gear rations. Table 10 shows steady state operation data. Figure 87 through 42 show transient operation with 150 KVA @ 0.95 PF and 75 KVA @ 0.75 PF. Most of the loads were on the PM system bus. The sequence of operation was 1. Parallel by closing the tie contactor. 2. Open the wound rotor system contactor. 3. Parallel via the WR line contactor. 4. Open the PM system contactor and 5. Parallel via the PM contactor.

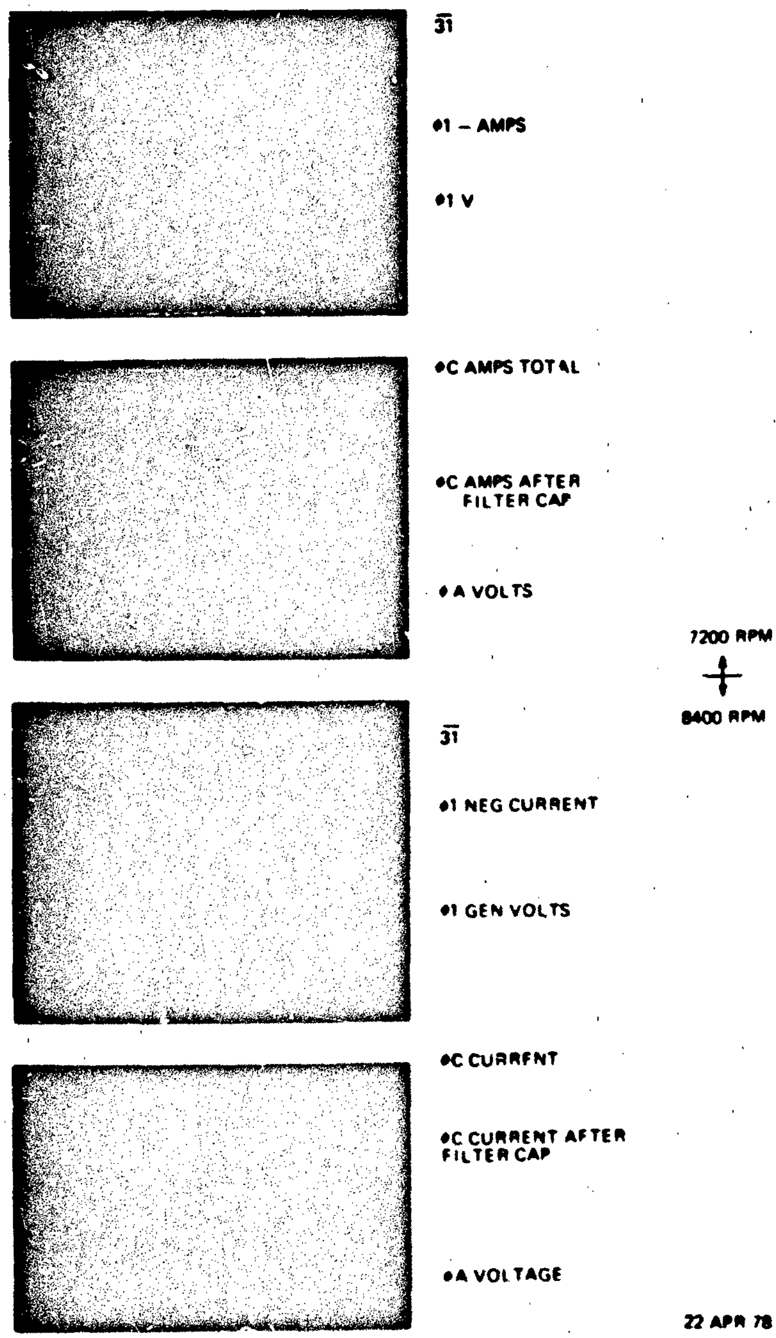


Figure 107. Start Mode Waveshapes Hi Speed

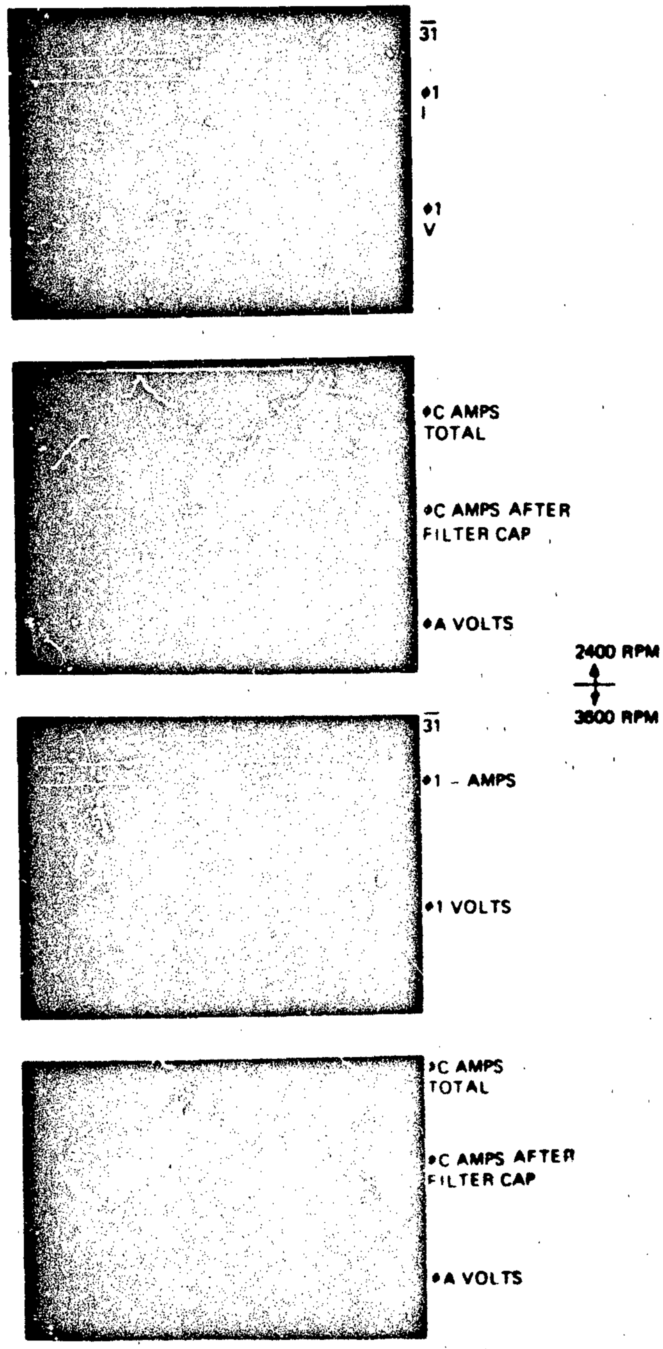


Figure 108. Start Mode Waveshapes Low Speed

TABLE 10

ELECTRICAL SYSTEM TEST DATA SHEET

GENERAL ELECTRIC BINGHAMTON, NEW YORK

Title of Test PARALLEL OPERATION OF 150 KVA SYSTEMS   Specification ______   Para ______   Test No ______   Sheet No ______

Generator Model No ______   Serial No ______
Converter/Control Model No ______   Serial No ______

TESTED BY DL AB[illegible]
DATE MAY 20 1975

NOTE NO	RDG NO	GEN SPEED RPM	TOTAL LOAD KW	TOTAL LOAD PF	VOLTAGE φA VOLTS	VOLTAGE φB VOLTS	VOLTAGE φC VOLTS	VOLTAGE φA-B VOLTS	VOLTAGE φB-C VOLTS	VOLTAGE φC-A VOLTS	CURRENT φA AMPS	CURRENT φB AMPS	CURRENT φC AMPS	WATTS/PHASE φA WATTS	WATTS/PHASE φB WATTS	WATTS/PHASE φC WATTS	HARMONIC CONTENT (%) φA	HARMONIC CONTENT (%) φB	HARMONIC CONTENT (%) φC	VOLTAGE MODULATION (V) φA	VOLTAGE MODULATION (V) φB	VOLTAGE MODULATION (V) φC	DC CONTENT (MV) φA	DC CONTENT (MV) φB	DC CONTENT (MV) φC	FREQ. HZ	CONTACTOR VDC	GENERATOR EG	GENERATOR IF	TRANSIENT
[illegible]	[illegible]	[illegible]	2		115.3	[illegible]	[illegible]	199.[illegible]	200.[illegible]	199.7	29	30	31	.11	2.6	2.5	2.7	2.4	2.4							400.0				
[illegible]		[illegible]									30	20	31	.37	[illegible]	[illegible]														
[illegible]			37.5	.75	115.3	115.2	115.2	199.0	200.[illegible]	199.9	48	46	47	3.0	3.3	1.3	1.7	1.6	1.5							400.1				
[illegible]											67	70	81	6.0	7.9	7.5														
[illegible]			75	.75	115.9	115.5	116.1	199.6	200.5	200.3	91	87	84	7.7	7.0	6.7	1.2	1.2	1.3							400.0				
[illegible]											124	117	139	11.5	11.4	13.4														
[illegible]			112.5	.75	115.9	115.7	115.3	199.6	200.3	200.0	197	198	198	12.5	13.2	13.0	1.5	1.9	1.9							400.0				
[illegible]											171	170	174	15.5	15.9	16.5														
[illegible]			150	.75	115.3	115.3	116.2	199.5	200.2	199.6	205	206	207	19.8	18.8	18.7	1.5	1.6	1.5							400.0				
[illegible]											221	220	223	19.8	19.9	20.5														
[illegible]			37.5	.95	115.1	115.0	115.4	199.8	199.5	199.7	45	35	34	4.9	3.6	3.0	2.3	1.7	1.8							400.0				
[illegible]											65	75	83	3.4	8.7	9.3														
[illegible]			75.0	.95	115.2	115.8	115.8	199.2	200.1	199.7	92	95	79	10.2	7.7	7.6	1.6	1.9	1.9							400.0				
[illegible]											113	137	135	11.6	10.4	15.6														
[illegible]			112.5	.95	115.0	115.9	115.3	199.3	200.5	200.1	198	172	135	12.0	15.5	15.5	1.8	1.4	1.5							400.0				
[illegible]											165	172	179	16.3	19.6	23.5														
[illegible]			150	.95	115.6	115.5	115.5	199.7	200.5	200.4	207	204	202	22.5	22.8	22.3	1.7	1.5	1.6							400.0				
[illegible]											217	217	223	24.6	24.6	25.5														

NOTES ______

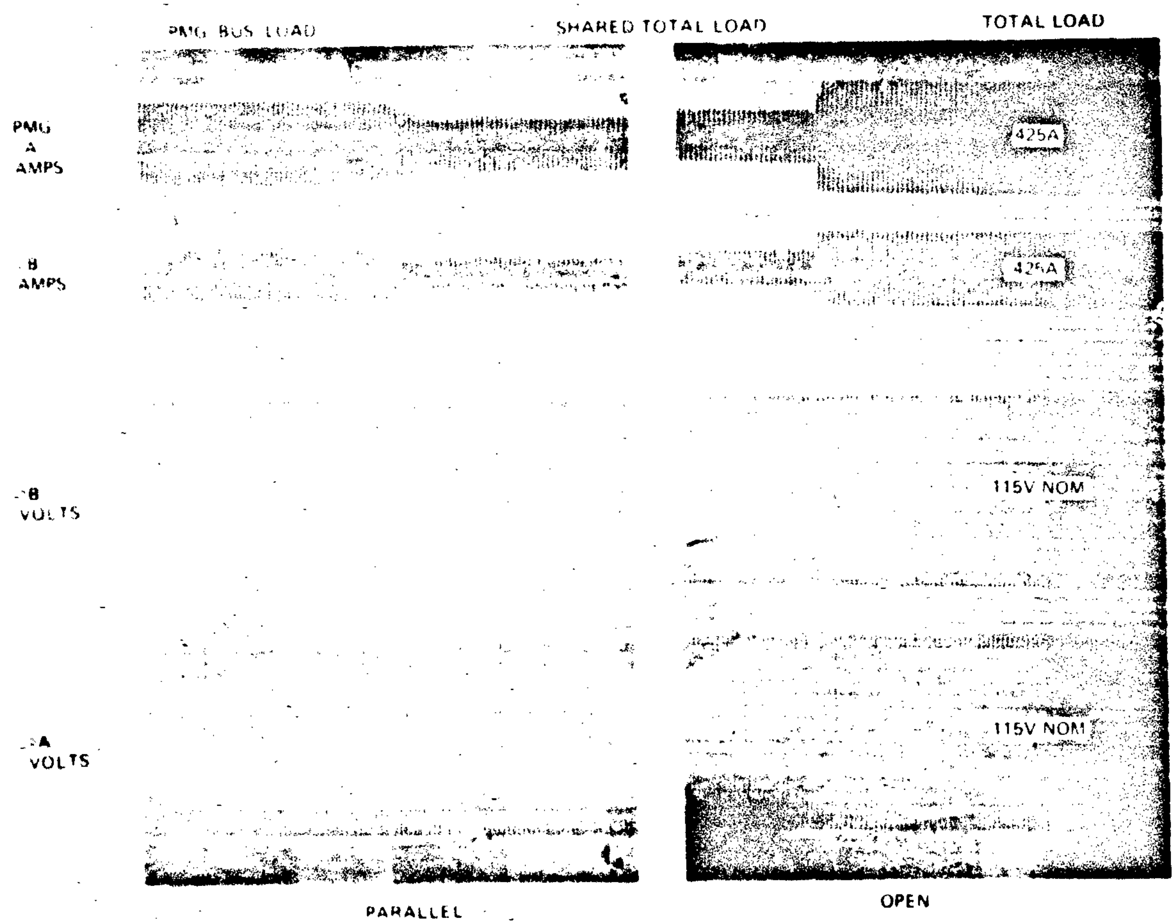


Figure 109 Transients - Tie Contactor Operation 150KVA @ .95 Pf

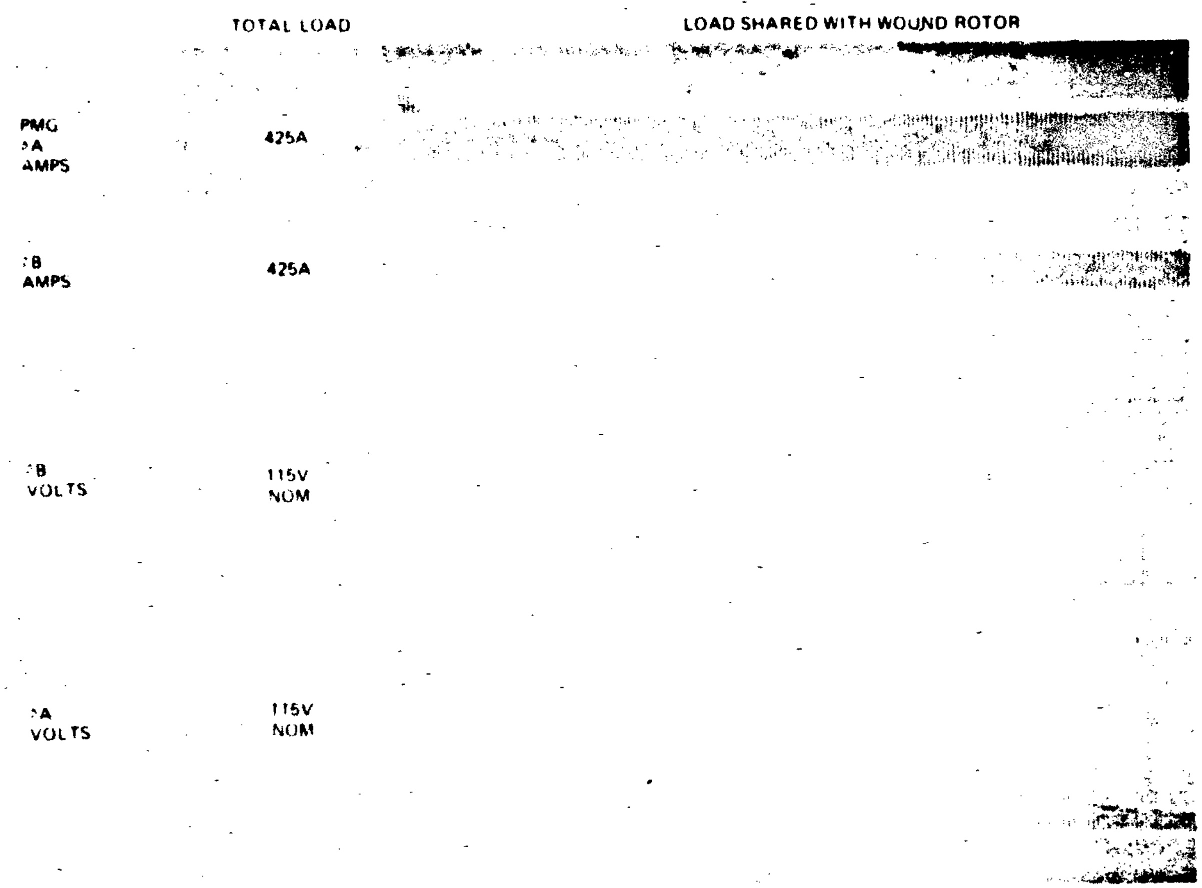


Figure 110. Transients - Parallel Across WR Contactor 150KVA .95Pf

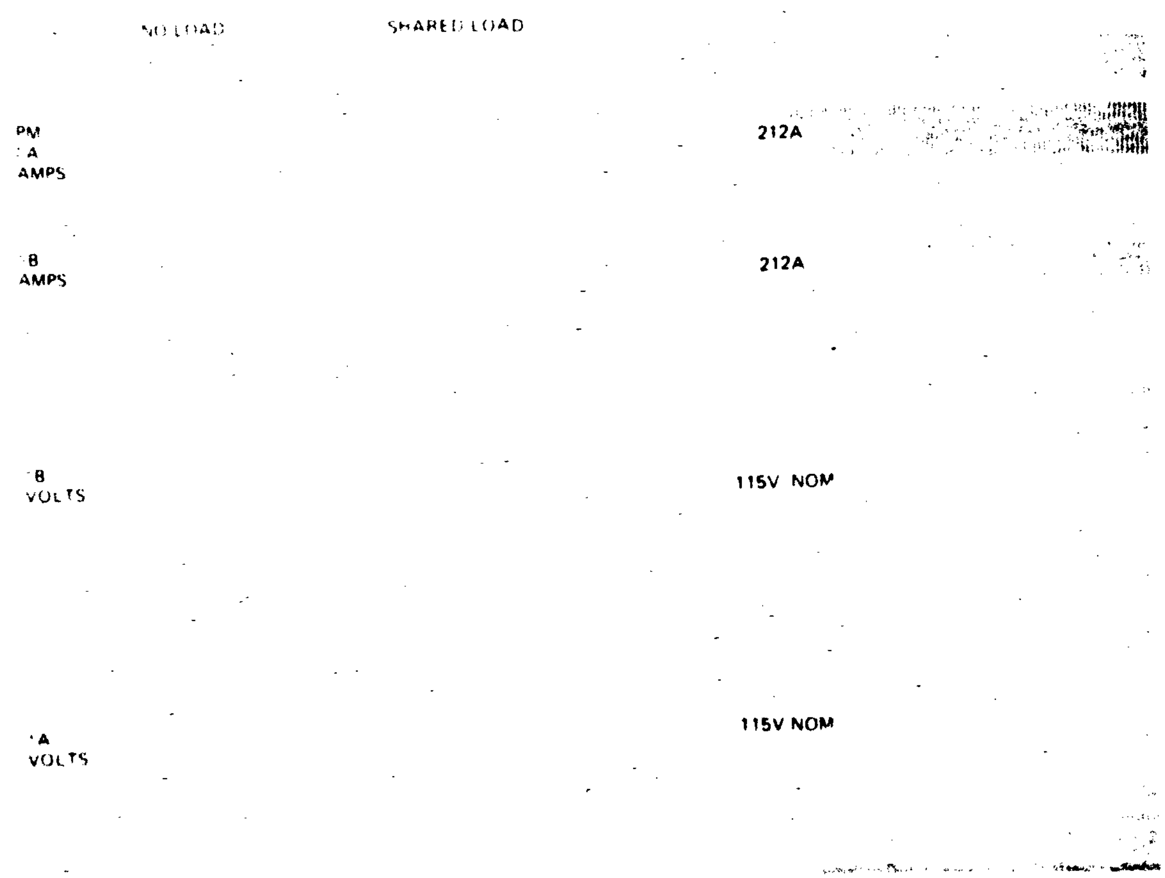


Figure 11[illegible] Transients - Parallel Across PM Contactor 150KVA @ .95 PF

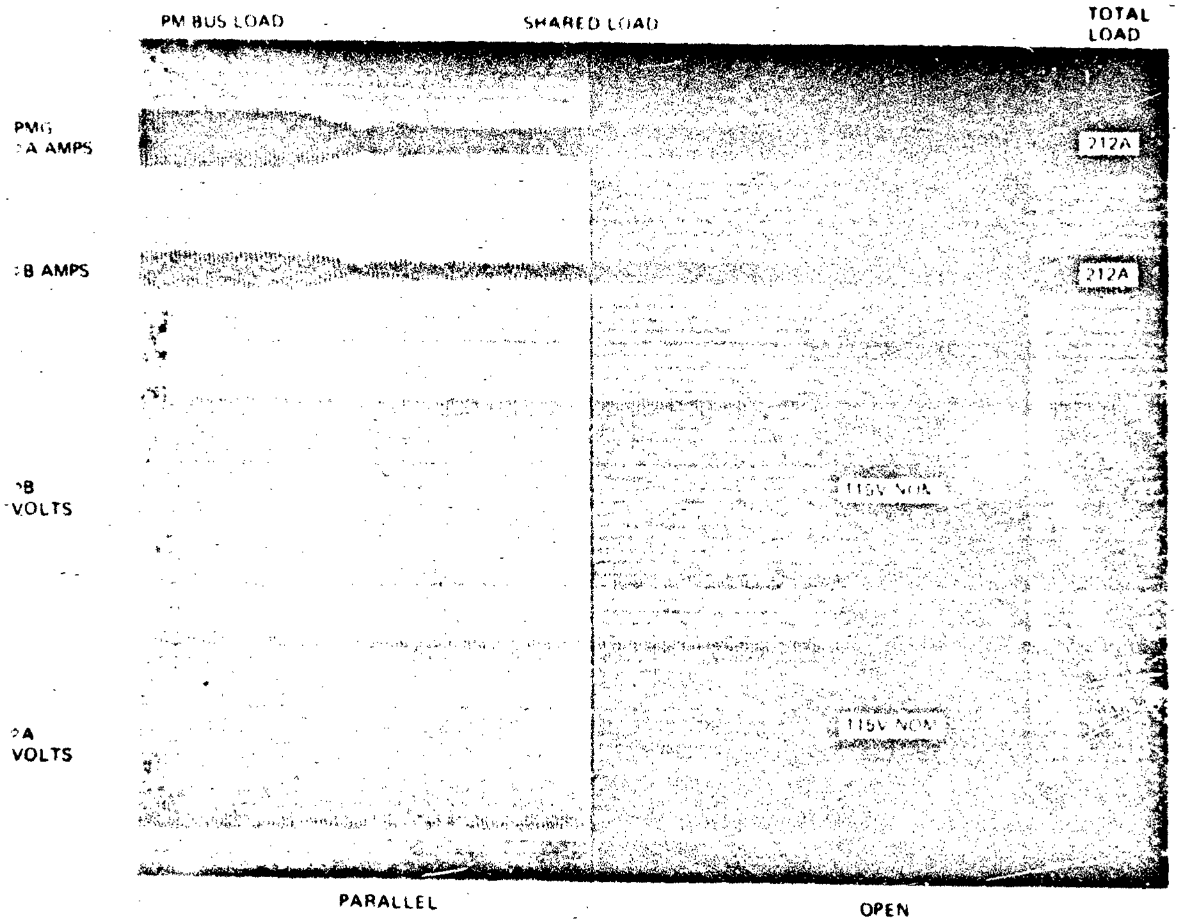


Figure 112. Transients - Tie Contactor Operation, 75KVA @ .75 Pf

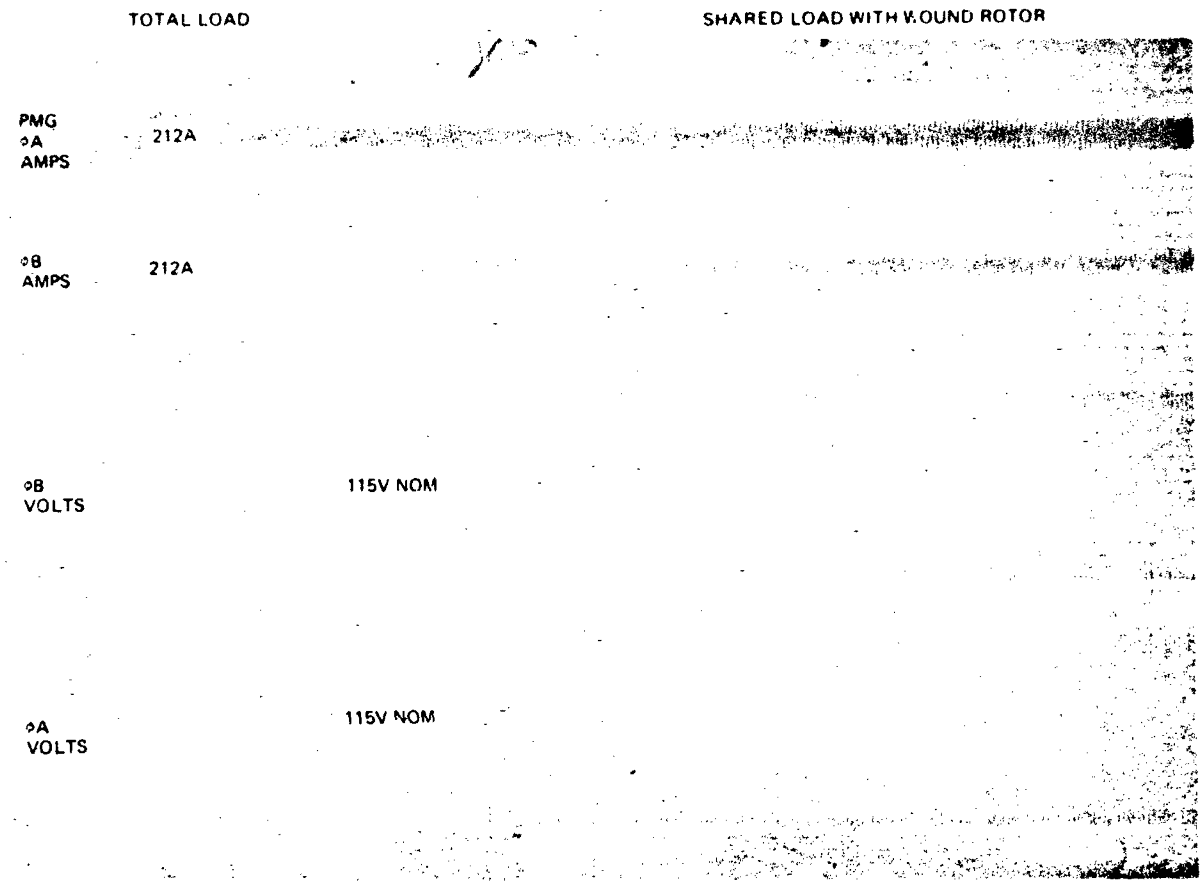


Figure 113. Transients - Parallel Across WR Contactor, 75KVA @.75 Pf

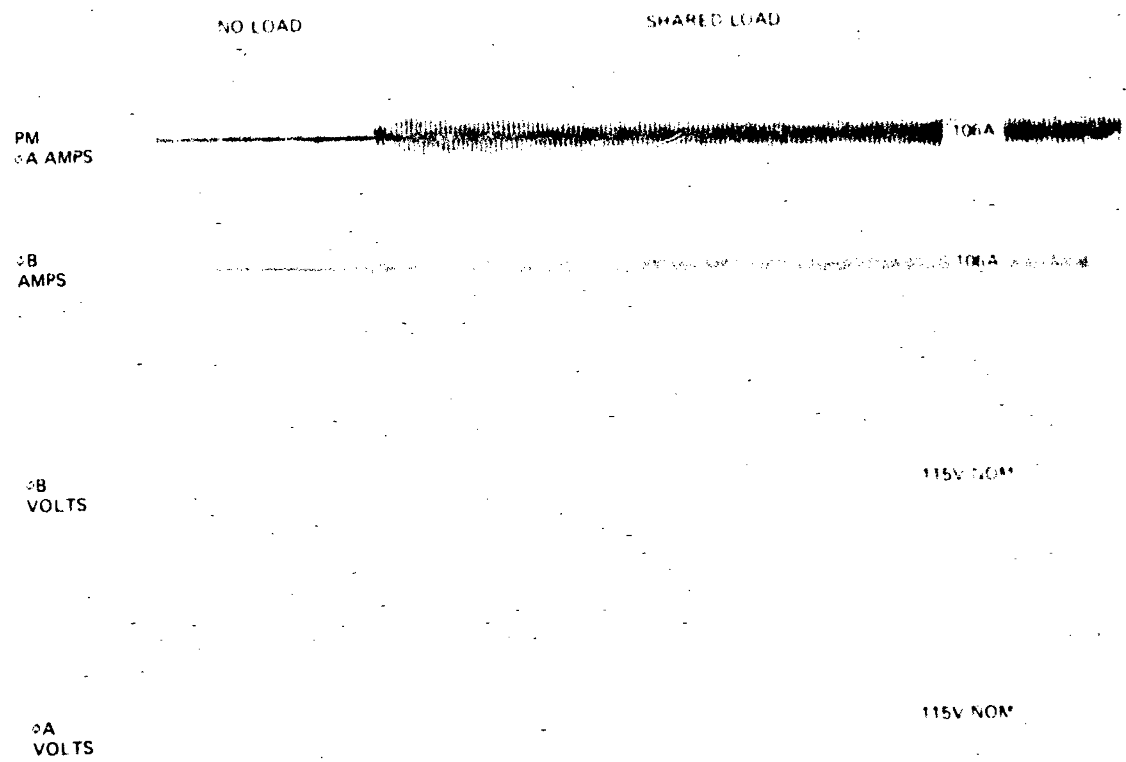


Figure 114. Transients - Parallel Across PM Contactor, 75KVA @ .75 Pf

ACS 11, 240

APPENDIX A

PHASE 3 TEST PLAN

FOR

150 KVA SAMARIUM COBALT VSCF STARTER-GENERATOR ELECTRICAL SYSTEM

CONTRACT NO.: F33615-74-C-2037
DATA ITEM: A004

GENERAL ELECTRIC

AIRCRAFT EQUIPMENT DIVISION BINGHAMTON, NEW YORK

1. INTRODUCTION

This test plan defines the testing to be performed on the 150 KVA Samarium Cobalt VSCF Electrical System in Phase 3 of Air Force Contract F33615-74-C-2037 and is submitted under Data Item A004 and in accordance with paragraph 5.1 of the contract Statement of Work. This includes preliminary tests on the starter-generator and the converter as individual units as well as the system checkout and performance testing.

2. EQUIPMENT IN TEST

2.1 PRIME

This is to be shipped as part of the contract.

1 - 150 KVA VSCF Samarium Cobalt Starter-Generator, Model Number 2CM404A1

1 - 150 KVA VSCF Converter, Oil Cooled Part Number 293E547

1 - Cooling system water to oil heat exchanger to cool converter Part Number TX6190

2.2 SECONDARY

This is Air Force property from Contract F33657-71-C-0811 to be returned after testing is completed.

1 - 150 KVA VSCF Wound rotor generator Model Number 2CM430A1

1 - 150 KVA VSCF Converter, Air Cooled Model Number 3S2060DF131A1

3. GENERATOR TESTS

3.1 GENERAL

The following tests will be run on the 2CM404A1 unless the results of a test show that further testing will appreciably degrade the generator performance or life.

The following instructions apply to all tests, unless otherwise specified:

> All rotating tests are to be made with 60°C oil-in (preferably without external oil heaters), and 100 psi oil pressure (or maximum oil pressure from the generator pumps). Air gap thermocouples will be limited to 200°C. If during any heat run there is a significant voltage droop, then remove load and reduce speed to obtain better cooling. If any of the above limits are exceeded, further instructions will be required.

After each heat run, a non-stabilized no-load test point at 4000 rpm is required. If there is a significant variation in the voltage from the test point (defined in Item #4 - Tests) further instructions will be required.

The vibration on the outboard end of the generator should not exceed 10 g during the test. If this limit is exceeded, contact the engineer for further instructions.

3.2 PHYSICAL INSPECTION

Inspect the generator to establish conformance with the specified dimensional requirements. Any discrepancies must be recorded and accepted by engineering before the generator proceeds to the tests of Section 3.3.

3.3 GENERATOR TEST PLAN

The generator testing sequence shall be as defined below:

1. **Obtain line-to-line and line-to-neutral resistances.**
2. **Hi-pot the ac winding line-to-ground at 1500 volts per test procedure EI 718A302FC.**
3. **Check the electrical-mechanical operation of the disconnect nonrotating. Apply power to the coil to determine the operation point. Check the mechanical reset mechanism.**
4. **Set the generator up on the drivestand and check the slow speed (4000 rpm) operation. Check oil flow, mechanical operation and no-load electrical performance. Check all phases for voltage balance. Record oil flow, oil temperature and thermocouple reading.**
5. **Increase speed in steps of 2000 rpm up to 12, 000 rpm. Stabilize temperature at each speed. Monitor voltages, waveshapes, phase relationship and temperatures during the stabilizing heat run and record stabilized test data.**
6. **At a speed that will maintain 120 volts line-to-neutral, run electrical loads at 1/4, 1/2, 3/4, 1 per unit rated current. Rated current is 140 amps per phase. Monitor and record all data indicated in Step 5.**
7. **Run no-load heat runs at 15, 000, 18, 000 and 21, 000 rpm. Monitor and record all data indicated in Step 5.**

8. After running the 21,000 rpm heat run, run a 5 m... 23,000 rpm overspeed test. Monitor and record all data ...ated in Step 5.

9. At 1/4, 1/2, 3/4, 1 per unit rated current at the spee... deter-mined in test 6, run four disconnect tests. Do not run a heat stabilized test.

10. Run a short circuit load point at 500 rpm initially to obtain the desired short circuit current, modify the speed to obtain 3 to 4 pu amps. Do not hold this load for more than 4 seconds. Connect an external oil system for cooling-lubrication and run the above test with cold oil. Run a 4000 rpm non-stabilized, no-load test (defined in Step 4) point as a final rotating test.

11. Disassemble and inspect the mechanical and electrical condition of the generator. Hi-pot stator winding at 1500 volts per test Procedure EI 718A302FC. Repeat resistance check as outlined in Step 1. Recheck the balance of the rotor to determine any change. Record if any unbalance.

At the completion of this testing, the generator is ready for testing with the converter.

4. CONVERTER TESTS

4.1 GENERAL

All tests defined below will be conducted under standard laboratory conditions unless otherwise stated in the specified test.

4.2 PHYSICAL INSPECTION

Inspect the converter to establish conformance with the specified dimensional requirements.

4.3 INSULATION TEST

With critical components removed from the converter assembly and with ground circuits removed from chassis termination, the dielectric strength will be tested by the application of a test voltage of 1500 vrms, 60 Hz, for one minute. Measure and record leakage current.

4.4 PRELIMINARY FUNCTIONAL TESTS

The following group of tests will be performed to establish functional integrity of the various subassemblies. The plug-in modulator cards will be removed for these tests to prevent firing of the power SCR's.

4.4.1 Power Supplies

With an external source of 28 vdc connected to the converter, measure and record the level of the internal low voltage power supplies.

a. +12 vdc
b. -12 vdc
c. + 8 vdc

4.4.2 Protection

Prior to system operation, all protective circuitry within the converter will be tested for operational integrity with the use of simulated system signals.

4 4.2.1 Internal Generator Fault

Measure and record the magnitude of differential current required to initiate and conclude a system trip by way of the DH protective circuitry.

4.4.2.2 Generator Overcurrent (GOC)

Measure and record the magnitude of generator current required to effect a system trip.

4.4.2.3 Starting Overcurrent (SOC)

Record the trip-level of current required to abort the engine starting sequence.

4.4.2.4 Feeder Fault (DL)

With a simulated fault condition applied within the low frequency differential protection zone, record the level of current (400 Hz) required to cause a system trip.

4.4.2.5 Load Division (DLC)

Record the magnitude of unbalanced current required by the protection circuit to the bus-tie relay.

4.4.2.6 Overvoltage (OV)

Record both the single phase and the three phase OV trip level.

4.4.2.7 Undervoltage (UV)

Record both UV trip levels.

4.4.2.8 Zero Sequence Voltage (ZV)

With simulated fault conditions, measure and record the zero sequence component of voltage required to cause a system trip.

4.4.2.9 DC Content (DC)

Apply a variable dc voltage (-500 mv to +500 mv) to the input terminals of the dc content detection circuitry and record the levels of both polarity signals that just causes trip action.

4.4.2.10 Waveform Distortion (WD)

With an applied signal, variable in both frequency and amplitude, at the input of the waveshaping feedback filter of 2 kc to 5 kc, measure and record the amplitude required to cause a system trip.

4.4.2.11 Auto Parallel (AP)

Determine the phase angle, frequency, and voltage amplitude required to enable the paralleling circuitry. Determine and record that the momentary parallel (gap) characteristics are within those established for AP.

4.4.3 Control Signals

With the converter connected to a prime power source (9 ϕ VSCF machine), check the following signals for timing (phase relationship), amplitude and regulation.

4.4.3.1 Frequency Reference Waves

With a simulated input dc control voltage, verify the regulation of each of the three phase, 400 Hz, waves. With the phase A vector as the reference, determine, with an oscilloscope, the phase displacement of phases B and C.

With an applied bias to the frequency control circuit and verify the frequency variation capability from 380 Hz to 420 Hz.

4.4.3.2 Firing Waves

Determine the phase relations of all firing waves with respect to its associated generator phase. Each of the nine firing waves lead its associated generator phase by 60 degrees. Record phasing.

Record the peak-to-peak voltage level of all firing waves at both base and top generator speed.

4.4.3.3 Blanking Waves

Observe each of the nine blanking waves for phasing and voltage levels. Each blanking wave is displaced from its associated firing wave by 90° (lagging). All voltage amplitudes are equal. Record.

4.4.4 Power Rectifier Test

The following group of evaluation tests will be performed to determine the electrical characteristics required of the despiker networks. The prime power source for these tests shall be the 150 KVA Samarium Cobalt VSCF Starter - Generator.

4.4.4.1 Rectifier DV/DT

With the generator at base speed and with the phase voltage regulator reference voltage depressed ($E_R = 0$), energize the 28 vdc and observe that each of the 54 power rectifiers are firing at $\alpha = 90^o$. Record the maximum rate of change of voltage observed at the SCR's.

4.4.4.2 Despiker Current

Under the same conditions as those in 4.4.4.1, measure and record the high frequency ripple currents (rms) in the despiker capacitors.

4.4.4.3 Despiker Dissipation

From current values obtained above, calculate the worst case dissipation in the despiker networks. At this point, the suitability of the despiker component values will be determined and required changes will be made.

4.4.5 Control Logic

4.4.5.1 Start Mode

Energize the control logic to initiate the start sequence and determine the functional integrity of the control circuitry.

4.4.5.2 Generate Mode

With the required input signals, simulated if necessary, determine the operational status of the generate control logic.

4.4.5.3 Power Mode Transfer

With simulated signals, as required, determine that the power-mode transfer circuitry is operating satisfactorily. Record starter cutout rpm.

5. ELECTRICAL SYSTEM TESTS

5.1 GENERAL

Following component tests of sections 3 and 4, the starter-generator and converter shall be connected together as a system and subjected to the tests defined below. All tests will be at standard laboratory conditions unless otherwise specified. Final performance data shall be recorded with generator inlet oil temperature at 115 to 120°C and converter inlet oil temperature at 65 to 70°C unless prior data indicates this would cause overheating and risk potential damage of the equipment.

5.2 GENERATE MODE - ISOLATED

With the converter and generator connected as a generating system, measure and record the following performance parameters under load conditions of no-load, rated 0.75 pf load, rated 0.95 pf load at each of three speeds: base, mid-range and top.

1. Line-to-neutral voltage (each phase)
2. Line-to-line voltage (each phase)

3. Voltage modulation (each phase)
4. Frequency (one phase only)
5. Frequency modulation (one phase only)
6. DC content (each phase)
7. Harmonic content - Total (each phase)

5.2.1 Efficiency

Measure at both base speed and at top speed, the generator input shaft torque and the total converter output power while operating at rated load, 0.75 pf; and at rated load, 0.95 pf. Calculate system efficiency under the four conditions.

5.2.2 Transient Response

Observe and record the voltage envelope (any phase) with the application and removal of 1.0 pu, 1.5 pu and 2 pu at both 0.75 and 0.95 power factor.

5.2.3 Fault Current

Measure and record the single phase L-N fault current of each of the three phases. With a three phase L-L-L-N short, measure and again record the short circuit current in each phase.

5.3 START MODE

For the start mode testing power will be supplied to the 293E547 converter from the output of the 150 KVA wound rotor generator VSCF system defined in Section 2.2.

5.3.1 Position Sensing

With simulated input signals, prior to attempting starts, observe the position sensing logic circuitry for proper operation. With the machine turning at low speed, observe the phase relationship of the three hall-probe outputs to their respective stator phase (adjustments to the hall-probe assembly should be made at this time, if required).

5.3.2 Start-Current Regulator

Energize the input current regulation circuitry with simulated voltage signals and determine that sufficient phase control can be accomplished to limit the input current to values equal to 1.5 pu.

5.3.3 Position Logic Shift

Determine by simulation the angular position shift versus speed with regard to best torque and commutation advantage. Make component adjustments for optimum performance. Determine, and make adjustments if necessary, to obtain the optimum position shift with regard to the counter-EMF of the machine being started.

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5.3.4 Motoring Test

With the start mode activated, measure and record the following parameters at each of the indicated speeds (generator shaft speeds). Hold each speed for a minimum of 30 seconds.

Torque
Input volts, amps, power
Total Harmonics
Position sense angle

Record all parameters at 0 rpm, 200, 600 and 1000 rpm; then at each 1000 rpm increments up to and including 11,300 rpm.

Compare these data with the starter torque requirements shown in Figure 2.* Plot torque versus rpm.

5.3.5 Engine Simulation (Starting Test)

With the engine simulator connected and calibrated to the starter shaft torque curve of Figure 2, record X-Y plots of input power (volts and amps), output torque (generator shaft), time versus shaft rpm up to 12,000 rpm. Compare to the starter torque requirements of Figure 2.

*Note that Figure 2 is equivalent to Figure 1 of the Work Statement (also Figure 1 in this test plan), but is in terms of the starter-generator shaft assuming a 4:3 gearbox starter to engine. This gearbox converts the engine idle speed of 9000 rpm to the starter-generator minimum speed of 12,000 rpm.

5.3.6 Engine Simulation - Hot Start, Duty Cycle

With the initial non-operating temperature of the starter-generator and converter stabilized at 125°F, perform the test defined in paragraph 5.3.5. Repeat the test of paragraph 5.3.5 a second and third time with a time interval of not more than two minutes between completion of one cycle and beginning of the next.

5.4 PARALLEL PREPERFORMANCE TEST

Prior to parallel system operation, with simulated signals as required, energize and evaluate the system compatibility requirements of each of the following functional blocks:

1. Phase-lock and frequency sync.
2. Parallel control logic
3. Load division loops

Adjust component values, if required, to optimize performance characteristics.

5.4.1 Speed and Load Characteristics

With the No. 2 system at a fixed speed, observe and record the following characteristics with the prime system at base, mid-range, and top speed; and under load conditions of no-load, 1.0 pu, 0.75 pf and 1.0 pu, 0.95 pf.

1. Voltage regulation
2. Voltage modulation
3. Frequency
4. Frequency modulation
5. DC content
6. Harmonic content

5.4.2 Load Division

Measure and record the total load currents of each system and the voltage of each system at its point of regulation. Record the total load KW and KVA.

Calculate the real and reactive difference load current from the above values. Record calculated values for each of the following speed and load conditions:

Loads

1. 0.5 pu at 0.75 pf
2. 0.5 pu at 0.95 pf
3. 1.0 pu at 0.75 pf
4. 1.0 pu at 0.95 pf

Speed

System #1	System #2
Base	Base
Base	Cruise
Base	Top
Cruise	Base
Cruise	Cruise
Cruise	Top
Top	Base
Top	Cruise
Top	Top

At each of the nine speed combinations, calculate and record the difference real and reactive load currents at each of t' e four load conditions listed.

5.4.3 Transient Response

Observe and record the voltage envelope at the sync bus during the application and removal of the following loads:

1. 0.5 pu at 0.75 pf
2. 0.5 pu at 0.95 pf
3. 1.0 pu at 0.75 pf
4. 1.0 pu at 0.95 pf
5. 1.5 pu at 0.75 pf
6. 1.5 pu at 0.95 pf
7. 2.0 pu at 0.75 pf
8. 2.0 pu at 0.95 pf

5.4.4 Fault Current and Overloads

Observe and record the voltage envelope at the sync bus during the application and removal of a short circuit at the load bus. Record the magnitude of fault current.

Apply 1.5 pu and 2.0 pu loads at 0.95 pf for 5 minutes and 5 seconds, respectively, to demonstrate compliance with the overload requirements of MIL-E-23001.

5.4.5 Protection Selectivity

With the two systems operating in parallel introduce simulated failure conditions to demonstrate the associated trip sequence. The system load for this test should be no greater than 0.5 pu load.

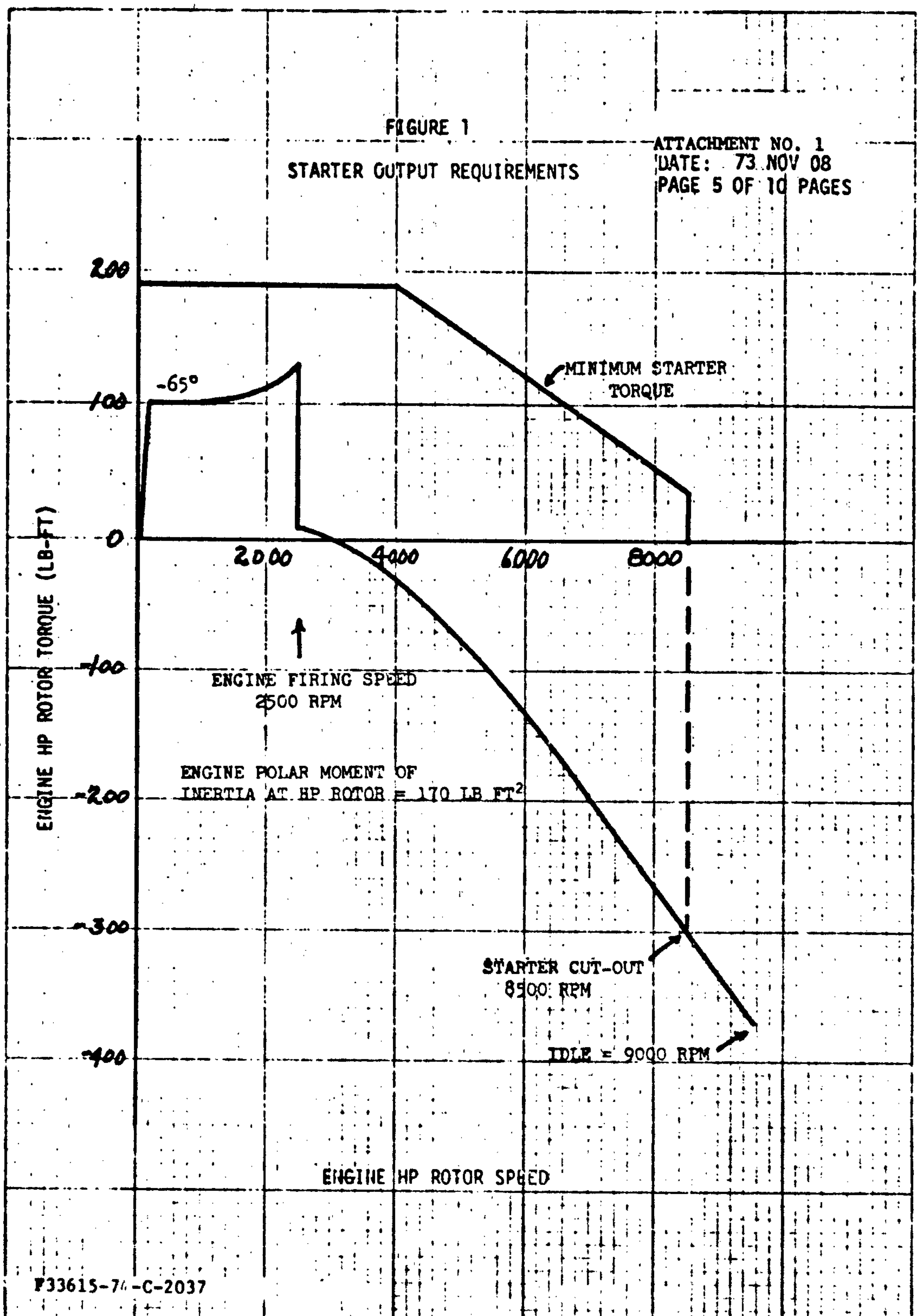

Figure A-1. Starter Output Requirements

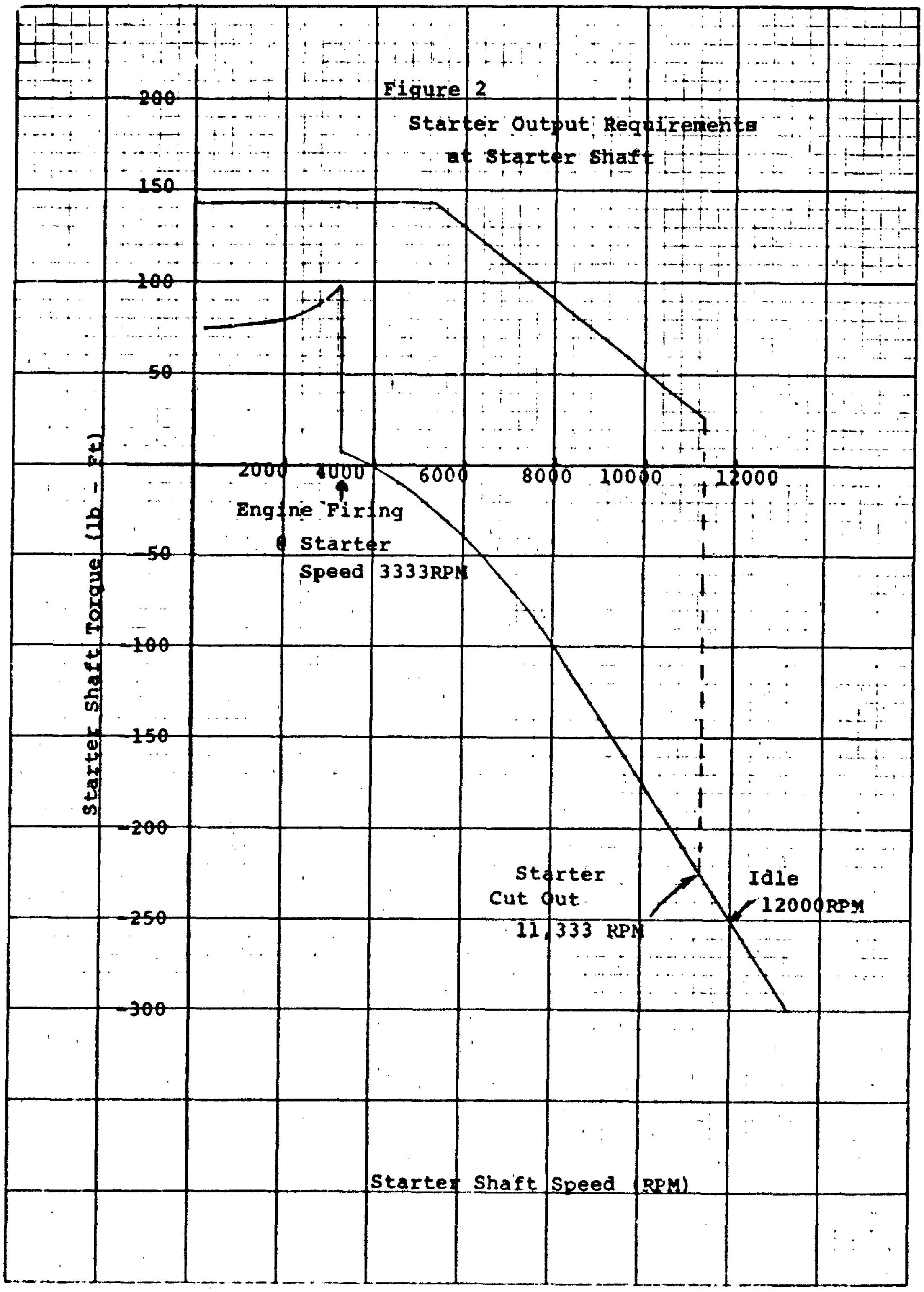

Figure A-2. Starter Output Requirements at Starter Shaft.

May 17, 1977

Proposed Changes To Phase 3 Test Plan ACS II 240 for the 150 KVA Samarium Cobalt VSCF.

1. Page 2 Paragraph 3.1 General

   Change the third paragraph to the following:

   "All rotating tests **are** to be made with 60°c oil-in (preferably without external oil heaters) and 100 psi oil pressure (or maximum oil pressure from the generator pump). Air gap thermocouple will be used to monitor approximate rotor temperature. I nitially this will be limited to 200°c but the limit may be increased if needed and approved by enginerring. If during any heat run there is a significant voltage droop, the load is to be removed and speed decreased to lower operating temperature."

2. Page 3 Paragraph 3.3 Generator Test Plan Delete Paragraph 3.3 and add the following:

   "<u>3.3 Electrical Inspection</u>

   Measure and record the line to neutral and line to line resistance of each phase. Measure and record the commutating reactance.

   HiPot each winding line to ground at 1500 Volts per test procedure EI 718A302 FC.

   <u>3.4 Generator Tests</u>

   The following series of tests are to be performed prior to operating the generator with the converter unless some are dropped due to potential damage to the machine.

   1. Check the operation of the disconnect mechanism non rotating. Slowly increase voltage and record voltage and current at operating point. Check the mechanical reset mechanism.

2. Set the generator up on the drivestand and check the slow speed (4000) operation. Check oil flow,Mechanical operation and no-load electrical performance. Check all phases for voltage balance. Record oil flow, oil temperature and thermocouple reading.

3. Increase speed in steps of 2000 rpm up to 12,000 rpm . Stabilize temperature at each speed. Monitor voltages waveshapes, phase relationship temperature and vibration level during the stabilizing heat run and record stabilized test data.

4. Adjust the load and speed to obtain a 60 kva output at approximately 155 volts line to neutral per phase. Monitor and record the data indicated in step 3 above. Operate the disconnect four times under this test condition.

5. Run no load heat runs as in step 3 above at 15,000 18,000 and 21,000 rpm.

6. Run at 23,100 rpm for 5 minutes monitoring and recording the data given in step 3 above.

7. Recheck the electrical inspection of paragraph 3.3 . Disassemble and inspect the mechanical condition of the machine recheck rotor balance.

8. Re assemble and repeat step 2 prior to testing with the converter."

3. Page 10 Paragraph 5.1 General

add an asterick to the last sentence followed by this note.

" * It is anticipated that rotor heating willlimit the performance range where 115 to 120^{0}c oil can be used so a significant portion of the final performance data may be taken with lower temperature generator cooling oil."

4. Page 11 Paragraph 5.2.1. Efficiency

Delete this paragraph as written and replace with the following:

"5.2.1. Efficiency

Record data to determine generator,converter and system efficiency at on half load .75pf, rated load .75pf and rated load .95pf for each of the following generator speeds 12,000 13,500, 15,000,16,500,18,000,19,500 and 21,000rpm. High frequency cable losses shall be estimated based on generator output current. Generator and converter losses may be established from heat rejection measurements.

5. Page 13 Paragraph 5.3.5 Engine Simulation (Starting Test)

In the first sentence change"Figure2" to "Figurel" and change "12,000" to "9000". Delete the second sentence and delete the note which refers to Figure 2 and a 4:3 gear box."

APPENDIX B

INSPECTION REPORT

DWG. NO.	ARTICLE	DATE	I. R. NO.
194E884	Generator, AC	16 Sept 77	368979

REV.	MODEL # / CAT #	CAUSE	LAST OPER. PERF.	I. SPEC.	TOT. QTY.	QTY. REJ.
	3 CM404A1				1	1

SHOP ORDER OR P.O. NO. | RESP. | OPERATOR AT FAULT | RECEIVED FROM

SN # | DEFECTS | PAGE 1 OF

1. RTV used to seal Bearing Bracket to frame wound. (Not specified) - DRAWING BEING CHANGED
2. Extra sleeve installed on pickoff leads.
3. Tape still on at leads as lead markers. HAS TO BE THERE!

(See next Page)

FOREMAN MFG.	FOREMAN. INSP.	INSPECTOR
		G Survey

THIS SAME DEFECT HAS OCCURRED ______ TIMES IN THE PRIOR ______ LOTS

CAUSE OF DEFECTS

MAT'L

LABOR

CORRECTIVE ACTION

SHIPPING NOTICE NO./DATE | GOV'T. INSP. REQUIRED YES ☐ NO ☐ | MRB ☐ PRELIM. REVIEW ☐

DISPOSITION OF PARTS

See above for defects for disposition.

DEFECTS ON ARTICLES ACCEPTED BY THIS IR DO NOT AFFECT THE SAFETY, PERFORMANCE, DURABILITY OR INTERCHANGEABILITY OF THE ARTICLES. SIGNED ______ DATE ______

MRB APPROVALS | ENGR/DATE | GOV'T REP./DATE | R & QA/DATE

ADDITIONAL COPIES TO:

MAIL TO: QUALITY CONTROL | GOV'T OFFICE | FOREMAN | INSPECTOR | Q. C. LAB. | COST

INSPECTION REPORT FOR NONCONFORMING ARTICLES

ITEM ______ BALANCE DUE ______

GOV'T CONTRACT # ______ G. E. REQ. # ______

SCRAP

AIRCRAFT CONTROLS ELECTRICAL SYSTEMS DEPT. — GENERAL ELECTRIC — 1200 LAWRENCE PARKWAY ERIE, PENNSYLVANIA 16501

4. Snap ring (pt. 66) not installed - TO BE INSTALLED WHEN ROTOR IS REWORKED.

5. Cover on ADE wiring (pt. 54) not installed. TO BE ASSEMBLED WHEN UNIT IS SHIPPED.

6. Braid frayed on ADE wiring. TO BE REWORKED WHEN UNIT IS PREPARED FOR SHIPMENT.

7. Parts 51 and 52 reversed. DRAWINGS TO BE CHANGED.

8. Terminal Block covers not installed. TO BE ADDED WHEN UNIT IS PREPARED FOR SHIPMENT.

9. Bearing support (pt. 14) - Bore opened .035, face machined down by .035. MARKED DRAWINGS IN DRAFTING - DRAWINGS WILL NOT BE REVISED UNTIL TESTING IS COMPLETE

10. Terminal block wired to marked up schematic. Not wired to revision C. DRAWING BEING REVISED.

11. Frame cut out in the area of part 69 to allow part to rotate. DRAWING BEING REVISED.

12. Temporary decals used. Nameplate and notation arrow omitted. Unit not painted. TO BE ADDED WHEN UNIT IS PREPARED FOR SHIPMENT.

13. Armature to magnet gap in cocked position (D-10) S/B .000 ± .001. Actual = .092. MARKED UP DRAWINGS IN DRAFTING. DRAWING WILL NOT BE REVISED UNTIL TESTING IS COMPLETE.

14. Unit has several thermocouples installed per separate instructions. PER CUSTOMER REQUEST

*U.S.Government Printing Office: 1979 — 657-002/579